**COVER**

*Barr'd Harbour, a small fishing village along the shore of St. John Bay, is the community from which Hank Woodard and his local guides departed to map the Highlands of St. John in the early 1950's. Rocks of the Labrador Group underlie the highlands and dip gently to the east. A fault scarp marks the western front of the highlands, the Ten Mile Lake fault striking through the country along a narrow saddle between the scarp and the two sharp ridges of steeply dipping rocks of the St. George Group. Rocks of the Lower Ordovician Watts Bight Formation occur along the rocky foreshore.*

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GEOLOGICAL SURVEY BRANCH
DEPARTMENT OF MINES AND ENERGY
GOVERNMENT OF NEWFOUNDLAND AND LABRADOR

# GEOLOGY OF CAMBRO-ORDOVICIAN ROCKS IN THE PORT SAUNDERS (NTS 12I/11), CASTORS RIVER (NTS 12I/15), ST. JOHN ISLAND (NTS 12I/14) AND TORRENT RIVER (NTS 12I/10) MAP AREAS

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# ABSTRACT

*Autochthonous lower Paleozoic platformal strata, approximately 1450 m thick, which are composed of siliciclastic and carbonate rocks, underlie the map area. Sedimentary rocks consist of the Labrador Group, of Early Cambrian age, overlain by Middle to Late Cambrian carbonates of the Port au Port Group. The Labrador Group unconformably overlies Grenvillian granite basement in the Highlands of St. John and along the western edge of the Long Range Mountains. Locally, marked relief occurs on the unconformity and a significant increase in thickness of basal Bradore sandstones occurs across northeast-trending faults to the north.*

*The Labrador Group comprises the Bradore, Forteau and Hawke Bay formations; they consist of arkosic and quartz–arenitic sandstones and shales, which are associated with limestones in the Forteau Formation. The lower Bradore Formation sediments were deposited in a non-marine fluviatile environment that was subsequently drowned by shallow-marine shelf and shoreline sediments of the upper Bradore and younger formations.*

*The overlying carbonates of the Port au Port Group include shales and dolostones of the March Point Formation, and dolostones, shales and minor limestones of the Petit Jardin Formation. Both formations represent deposition in shallow peritidal settings.*

*Limestones and syngenetic and diagenetic dolostones of the St. George Group conformably overlie the Cambrian rocks. The St. George Group consists of the Watts Bight, Boat Harbour, Catoche and Aguathuna formations of early Canadian to early Whiterockian age. The strata were deposited in open subtidal shelf and shallow shoreline settings. Widespread development of cryptalgal mounds occurs in both settings.*

*The rocks of the St. George Group were laid down in two major depositional sequences that reflect long-term transgression and regression upon the platform. The older megacycle includes the Watts Bight Formation and lower member of the Boat Harbour Formation; the younger magacycle includes rocks of the Barbace Cove Member, Boat Harbour Formation and the Catoche Formation. A disconformity occurs at the top of each magacycle. The older disconformity is regionally widespread and seperates early Canadian (Tremadocian) strata from late Canadian (Arenigian) strata. The unconformity at the top of the Catoche Formation is also a major regional feature. In the map area, thin (5 to 15 m) Whiterockian dolomitic carbonates of the upper member of the Aguathuna Formation rest unconformably upon late Canadian Catoche Formation dolomites. The Aguathuna Formation is one-fifth of its thickness elsewhere in western Newfoundland. This, plus the absence of the lower member of Aguathuna Formation of late Canadian age due to early Whiterock erosion, and the presence of northeast-trending late Canadian age faults and joints cutting the Catoche Formation and filled by Aguathuna sediments, indicate that the Port au Choix area was an eroded, structural high during the late Canadian–early Whiterockian.*

*Diagenetic and epigenetic dolomites are extensively developed in each of the formations of the St. George Group and collapse(?) breccias are common in the Boat Harbour Formation.*

*The St. George Group is conformably overlain by cyclic, fenestral and massively bedded limestones of the Middle Ordovician Table Point Formation (Table Head Group). The peritidal- to subtidal-shelf limestone of the formation preserve the record of Middle Ordovician transgression in the area.*

*The generally gently dipping strata of the area are cut by a major system of braided, curvilinear, northeast-trending, high-angle faults. Vertical throws of large magnitude (100 to 1500 m) occurred on many of the faults but fold structures and trends, inverted bedding and stratigraphic relationships suggest that the fault system was also affected by oblique-slip movements.*

*Dolomites of the Port au Port and St. George groups host several small galena–sphalerite showings. Galena and sphalerite are also hosted by petroliferous dolomites that replace limestones of the Table Head Group. Minor barite, fluorite and pyrite also occur in the area. The area contains huge reserves of potassium-rich shale, quartz-rich sandstone, and metallurgical dolomite and limestone.*

# INTRODUCTION

Geological mapping of the Cambro-Ordovician platformal rocks of the Great Northern Peninsula, at a scale of 1:50 000, by the Newfoundland Department of Mines and Energy commenced in the Port au Choix–Hawkes Bay area during the summer of 1982. This area, with its good coastal exposure and stratigraphic continuity, has formed an important link in the understanding of the stratigraphy of the lower Paleozoic strata of western Newfoundland since the earliest geological examination of the peninsula in the 1860's (Logan, 1863). It was first visited by the author in 1976 and again in 1977 (Knight, 1977, 1978); it is these early studies and including the mapping and stratigraphic studies carried out in 1982, which form the basis for this report. The mapping was done by foot traverses; measured sections used a metre ruler, a 100 m tape and paced intervals. Fossils (mainly trilobites) were collected (Boyce, 1983a, 1983b, 1985) as were kilogram-sized rock samples of horizons that yielded trilobites for further biostratigraphic study.

## GEOGRAPHIC SETTING

Mapping covered contiguous areas of the Castors River, St. John Island, Port Saunders and Torrent River map sheets (Figure 1). The area is heavily wooded, and includes substantial areas of forest cutovers, windfalls and dead timber, new forest growth and tuckamore spruce. Large, open marshes occur on the New Ferolle and Castor Point peninsulas, in areas east of Port au Choix and south of Western Brook Pond. Cambrian and Ordovician carbonates underlie a low terrane up to 75 m high, along the west and south sides of the map area. The low terrain consists of broad ridges separated by flat, narrow, fault- or bedding-controlled valleys of forest or marsh. Narrow steep-sided ridges occur just west of the Highlands of St. John.

The Highlands of St. John, in contrast, form an upstanding plateau of 480 m elevation underlain by almost flat-lying rocks of the Labrador Group. An impressive west-facing scarp, related to the Ten Mile fault, forms the front of the plateau only a few kilometres from the shores of St. John Bay. The plateau is divided into the north and south summits by Doctors Brook, which is incised to a depth of 300 m, as it drains westward into the bay. Blocky felsenmeer, derived from break-up of the Hawke Bay Formation, blankets the top of much of the plateau of the highlands. Some spectacular horseshoe-shaped waterfalls, which are cut in rocks of the Forteau Formation, occur along Doctors Brook and where tributary streams flow off the plateau north of Doctors Brook. Flat-topped, oval to rounded mountains, up to 500 m high, occur at the western margin of the Long Range Mountains in the east of the map area. These mountains are underlain by gently inclined rocks of the Labrador Group and overlook the more rugged mountainous terrain of the Long Range Mountains that stretchs away to the east of the map area.

Outcrop is best exposed on the wooded, rarely barren, slopes of the ridges; it may also be found at the bottom of sink-holes that occur in the low-lying wooded and marshy valleys. Areas east of Route 73 and northeast of Eddies Cove West have poor outcrops, due to either the thick forest growth and/or extensive marsh development. Drift cover is generally only a few metres thick except in the areas to the east of Port Saunders where tens of metres of coarse glacial debris (and locally some sand dunes) fill major fault-controlled valleys. Grey, fossiliferous, marine clays underlie the low areas near Hawkes Bay. An impressive raised beach (Plate 1), composed of boulder-sized clasts derived from the underlying Hawke Bay quartzite, occurs at 130 m elevation on the southwestern flank of the Highlands of St. John (Cumming and Grant, 1974).

In the north and centre, the coast is rocky and irregular, consisting of small pocket boulder and sandy beaches, coves and rocky promontories. Large east-trending, sheltered bays occur in the south.

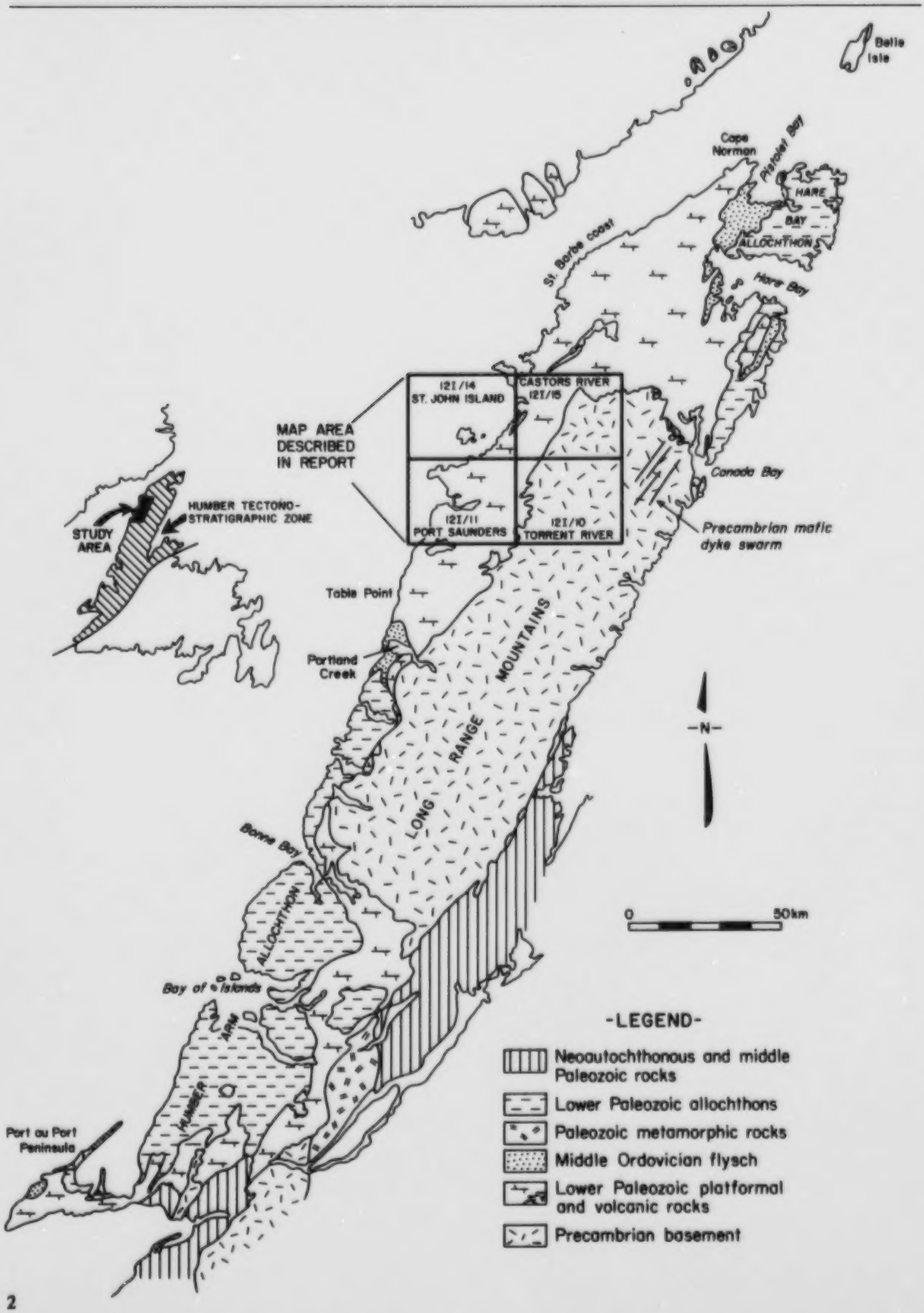
Access to the map area from Deer Lake is provided by the Viking Highway (Route 73). Gravel and paved branch roads link the main communities of River of Ponds, Hawkes Bay, Port Saunders, Port au Choix, Bartlett's Harbour, and Reefs Harbour. Hawkes Bay, Port au Choix and Port Saunders are the main settlements in the area, providing accommodations, groceries and other provisions. Port au Choix is a prosperous fishing community, which also hosts a Maritime Archaic Indian burial site and Dorset Eskimo settlement, both preserved as historic sites by Parks Canada.

Access to the rest of the map area is facilitated by a network of forest access roads of variable quality. Large lakes, such as Western Brook Pond (locally referred to as 'Wes Lake'), Eastern Blue Pond (locally known as 'Bluey') and River of Ponds Lake, provide access to the more remote areas by small boat. Helicopter provides the best access to mountainous areas in the east and northeast.

## PREVIOUS WORK

The map area is important because it contains the type area where, in 1861, James Richardson proposed several rock divisions in lower Paleozoic platformal strata that Logan (1863) assigned to the Quebec Group. In particular, divisions E to L (Table 1) were compiled from Bustard Cove to the Port au Choix and Pointe Riche peninsulas. Fossils collected by Richardson were catalogued and described by Billings (1865).

The divisions of Richardson (*in* Logan, 1863), continued to form the framework for discussion of the lower Paleozoic sequence of western Newfoundland by subsequent workers, even though, as will be shown, different divisions contain strata of the same rock unit. In the forefront of this work was the memoir of Schuchert and Dunbar (1934) and an unpublished Newfoundland government report by Johnson (1949). Schuchert and Dunbar (1934) proposed the first


Belle Isle
Cape Norman
Pleasant Bay
HARE BAY ALLOCHTHON
St. Barbe coast
Hare Bay
121/14 ST. JOHN ISLAND
CASTORS RIVER 121/15
MAP AREA DESCRIBED IN REPORT
121/11 PORT SAUNDERS
121/10 TORRENT RIVER
Canada Bay
Precambrian mafic dyke swarm
HUMBER TECTONO-STRATIGRAPHIC ZONE
STUDY AREA
Table Point
Portland Creek
LONG RANGE MOUNTAINS
-N-
Bonne Bay
ALLOCHTHON
0
50km
Bay of Islands
HUMBER ARM
Port au Port Peninsula
-LEGEND-
Neoautochthonous and middle Paleozoic rocks
Lower Paleozoic allochthons
Paleozoic metamorphic rocks
Middle Ordovician flysch
Lower Paleozoic platformal and volcanic rocks
Precambrian basement

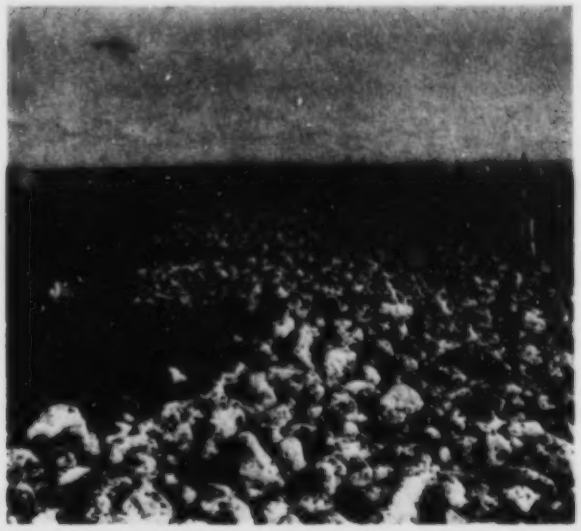


**Plate 1.** *Raised boulder beach, 130 m above sea level, southern end of the Highlands of St. John.*

modern stratigraphic terminology of western Newfoundland, much of which has become entrenched in geological literature. They named and described Lower Cambrian rocks in both southern Labrador and the Highlands of St. John, which they assigned to the Labrador Series. Included in this series, are Richardson's divisions A to C (Table 1) of the Potsdam Group of Logan (1863), which they called Bradore, Forteau and Hawke Bay formations, respectively. However, included in their Hawke Bay Formation, was an upper sequence of carbonate rocks, which are now known to be of younger Cambrian age. The sequence was subsequently separated (Knight, 1977) from the formation and the Labrador Group, as the series was subsequently called (Nelson, 1955; Woodard, 1957; Knight, 1977, 1978). Schuchert and Dunbar (1934) included strata consisting of Richardson's divisions D to K, in the Lower Ordovician St. George Series. These divisions were later called the St. George Group by Johnson (1949), who extensively studied the Cambro-Ordovician strata and fossils. Schuchert and Dunbar (1934) assigned the Middle Ordovician limestones (division L, of Richardson) to the Table Head Series, which later became known as the Table Head Group (Nelson, 1955; Woodard, 1957; Klappa *et al.*, 1980) or the Table Head Formation (Whittington and Kindle, 1963, 1969; Stouge, 1980, 1982).

The first geological maps of the area were those of Nelson (1955) and Woodard (1957). Nelson (1955) included the area north of Hawkes Bay to Port au Choix in a 1:100 000-scale map that continued as far south as Portland Creek. Woodard (1957) produced a 1:100 000-scale map of the area from Port au Choix to Castors River. Woodard correctly separated the St. George Group from the Labrador Group across his Sandy Bay fault (here called the Ten Mile Lake fault). Both Nelson (1955) and Woodard (1957) included fairly detailed discussions of the Labrador Group. Woodard subdivided the Bradore Formation into two lithological members (Table 1). Both authors followed Schuchert and Dunbar (1934) and included in the Hawke Bay Formation the carbonates that lie above the white quartzites. Neither worker added anything substantial to the division and understanding of the Ordovician carbonates of the St. George and Table Head groups. In fact, Woodard incorrectly interpreted rubbly weathering limestones of the St. George Group that outcrop along the shore of Bustard and Old Man coves as the Table Head Group. Woodard (1957) placed some of the Table Head limestones in a formation he called the Well Cove Formation. Part of the area is also included in a recent memoir and 1:125 000-scale compilation map of the northern part of the Great Northern Peninsula (Bostock *et al.*, 1983); Smyth (1982) also compiled the geology of the area at a scale of 1:250 000.

Research into the lower Paleozoic rocks of the area was resumed in the 1970's, partly in response to the economic impetus provided by development of the sphalerite deposit at Daniel's Harbour to the south. Kluyver (1975), Knight (1977, 1978), Levesque (1977), Pratt (1979) and Pratt and James (1982, 1986) examined various aspects of the sequences. This work has led to the subdivision of the succession in the St. George Group especially in the immediate area of Port au Choix and Eddies Cove West (Table 1).

Kluyver (1975), studying the section of the St. George Group near Port au Choix, divided the succession into the Barbace Point, Catoche and Port au Choix formations. Unfortunately, the Barbace Point Formation is incompletely exposed here and affected by widespread epigenetic dolomitization. Rocks he also assigned to the Port au Choix Formation include dolostones that replaced the top of the Catoche Formation, and a thin capping unit of microcrystalline dolostone that belongs to the Aguathuna Formation. Soon thereafter, Knight (1977, 1978) studied the same rock sequences and other sections of the St. George Group near Cape Norman and Table Point. He removed the carbonate rocks from the Hawke Bay Formation (which he informally called the Hawke Bay quartzite formation) and proposed several informal rock units within the overlying carbonate succession. Three formations were noted in the carbonates of Cambrian age, although Knight (1980b) later preferred to reduce this to two formations. In the St. George Group, five rock units were originally delineated by Knight (1977, 1978). However, more recently, the sequence was divided into only four formations (Knight, 1983; Knight and Boyce, 1984; Knight and James, 1988). The fifth rock unit, which consists of diagenetic dolostones and which Knight had called 'diagenetic carbonates' (Knight, 1977, 1978), is now included in the Catoche Formation (Knight and James, 1988). Knight (1977) provided some preliminary analysis of

**Figure 1.** *Geological terranes in western Newfoundland and location of the study area described in this report.*

TABLE 1. STRATIGRAPHIC NOMENCLATURE FOR CAMBRIAN AND ORDOVICIAN ROCKS, PORT AU CHOIX AREA

| LOGAN 1863 (RICHARDSON'S DIVISIONS) | | SCHUCHERT & DUNBAR 1934 | | NELSON 1956 WOODARD 1957 | | KLUYVER 1975 | | LEVESQUE 1977 | | KNIGHT 1977 | | KNIGHT 1978 1980 | | PRATT 1979 PRATT & JAMES 1982 | | KLAPPA et al, 1980 KNIGHT & JAMES 1988 KNIGHT THIS REPORT | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| QUEBEC GROUP | N | TABLE HEAD SERIES | UPPER | TABLE HEAD GROUP | WELL COVE FM | TABLE HEAD GROUP | | | | TABLE HEAD FORMATIONS | | TABLE HEAD GROUP | | | | TABLE HEAD GROUP | CAPE CORMORANT FM |
| | M | | MIDDLE | | | | | | | | | | | | | | BLACK COVE FM |
| | L | | LOWER | | | | | | | | | | | | | | TABLE COVE FM |
| | | | | | | | | | | | | | | | | | TABLE POINT FM |
| | I | ST. GEORGE SERIES | | ST. GEORGE GROUP | | ST. GEORGE GROUP | PORT AU CHOIX FM | ST. GEORGE FORMATION | UPPER CYCLIC MBR | ST. GEORGE GROUP | SILICEOUS DOLOMITE FM | ST. GEORGE GROUP | BELLBURNS FM | ST. GEORGE GROUP | AGUATHUNA FM | ST. GEORGE GROUP | AGUATHUNA FM |
| | H | | | | | | CATOCHE FM | | MIDDLE LIMESTONE MBR | | DIAGENETIC CARBONATE | | CATOCHE FM | | CATOCHE FM | | CATOCHE FM |
| | G | | | | | | BARBACE POINT FM | | | | CATOCHE FM | | BOAT HARBOUR FM | | ISTHMUS BAY FM | | BOAT HARBOUR FM |
| | F | | | | | | | | LOWER CYCLIC MEMBER | | | | | | | | |
| | E | | | | | | | | | | WATTS BIGHT FM | | WATTS BIGHT FM | | | | WATTS BIGHT FM |
| | D | | | | | | | | | | UNFORTUNATE COVE FM | PORT AU PORT GROUP | PETIT JARDIN FM | | | PORT AU PORT GROUP | PETIT JARDIN FM |
| | | LABRADOR SERIES | HAWKE BAY FM | LABRADOR GROUP | HAWKE BAY FM | | | | | | DOLOMITE FM | | | | | | |
| | | | | | | | | | | | MICRITE FM | | MARCH PT. FM | | | | MARCH PT. FM |
| POTSDAM GROUP | C | | | | | | | | | LABRADOR GROUP | HAWKE BAY FM | | | | | LABRADOR GROUP | HAWKE BAY FM |
| | B | | FORTEAU FM | | FORTEAU FM | | | | | | FORTEAU FM | | | | | | FORTEAU FM |
| | A | | BRADORE FM | | BRADORE FM CAIN'S HUMBUG BROOK MBR TWO MILE POND MBR | | | | | | BRADORE FM | | | | | | BRADORE FM |

sedimentation. As a result, Knight (1978) proposed that there was a broad framework of platformal build-up suggested by the stratigraphy and style of sedimentation that composes the lower Paleozoic carbonate platform. This build-up was controlled by three megacycles of transgression and regression. More detailed discussion of sedimentation of the Cambro-Ordovician carbonate succession by Levesque (1977) included the important sections near Port au Choix. Pratt (1980) provided further detailed analysis of cryptalgal structures (see also Pratt and James, 1982), lithofacies, depositional environment and diagenesis of rocks in the St. George Group including rock sequences in the map area. Cryptalgal structures were described by Pratt and James (1982) from the Watts Bight, Boat Harbour (strata assigned by them to the Isthmus Bay Formation) and Catoche formations; calcareous algae, sponges and primitive corals were documented as important components of thrombolitic mounds. Treatment of the rocks is generally scant in the recent memoir of Bostock *et al.* (1983). Cumming (*in* Bostock *et al.*, 1983), who described the lower Paleozoic autochthonous strata, heavily utilized previous work and proposed no new stratigraphic subdivisions except the Cambrian Eddies Cove Formation, which here is subdivided into the March Point and Petit Jardin formations.

The Table Head Group has also been studied on the Pointe Riche Peninsula (Whittington and Kindle, 1969; Stouge, 1980; Klappa *et al.*, 1980; Klappa and James, 1980), where the lower limestones of Schuchert and Dunbar (1934) belong to the Table Point Formation of Klappa *et al.* (1980). Although there is a general agreement of formations and group boundaries by these workers, nomenclature is nevertheless variable (Table 1).

Trilobites (Whittington and Kindle, 1969; Boyce, 1979, 1983, 1985; Fortey, 1979), conodonts (Stouge, 1980, 1982; Stouge and Boyce, 1983), cephalopods (Flower, 1978) and graptolites (Cumming, 1967; Skevington, written communication in Lopej, 1977) have been described from the St. George and Table Head groups of the Port au Choix and Pointe Riche peninsulas.

Exploration for Pb–Zn prospects has spanned two decades. New Jersey Zinc Limited explored the area northeast of Eddies Cove West and near Pikes Feeder Pond over ground underlain by strata from the St. George, Port au Port and Labrador groups (Shearer, 1964; Beckett, 1966). Brinex Limited explored the area near Port au Choix and Hawkes Bay (Coope and van de Poll, 1965; Kluyver, 1973; Lopej, 1977; Smith, 1973; Dickie and Lyn, 1979; Ryder, 1979). Although some Pb and Zn soil geochemical anomalies are known from the area, only one minor sphalerite showing in the area near Eddies Cove West (Shearer, 1964; Beckett, 1966) has so far been discovered; galena, sphalerite and chalcopyrite are known from rocks of the Port au Port Group near Pikes Feeder Pond. Some scattered exploratory drilling by Tecam Limited (1975) occurred in the southern part of the Port Saunders map area. Regional lake-sediment geochemical surveys by the Newfoundland Department of Mines and Energy (Davenport *et al.*, 1974a; Butler and Davenport, 1982) included the map area.

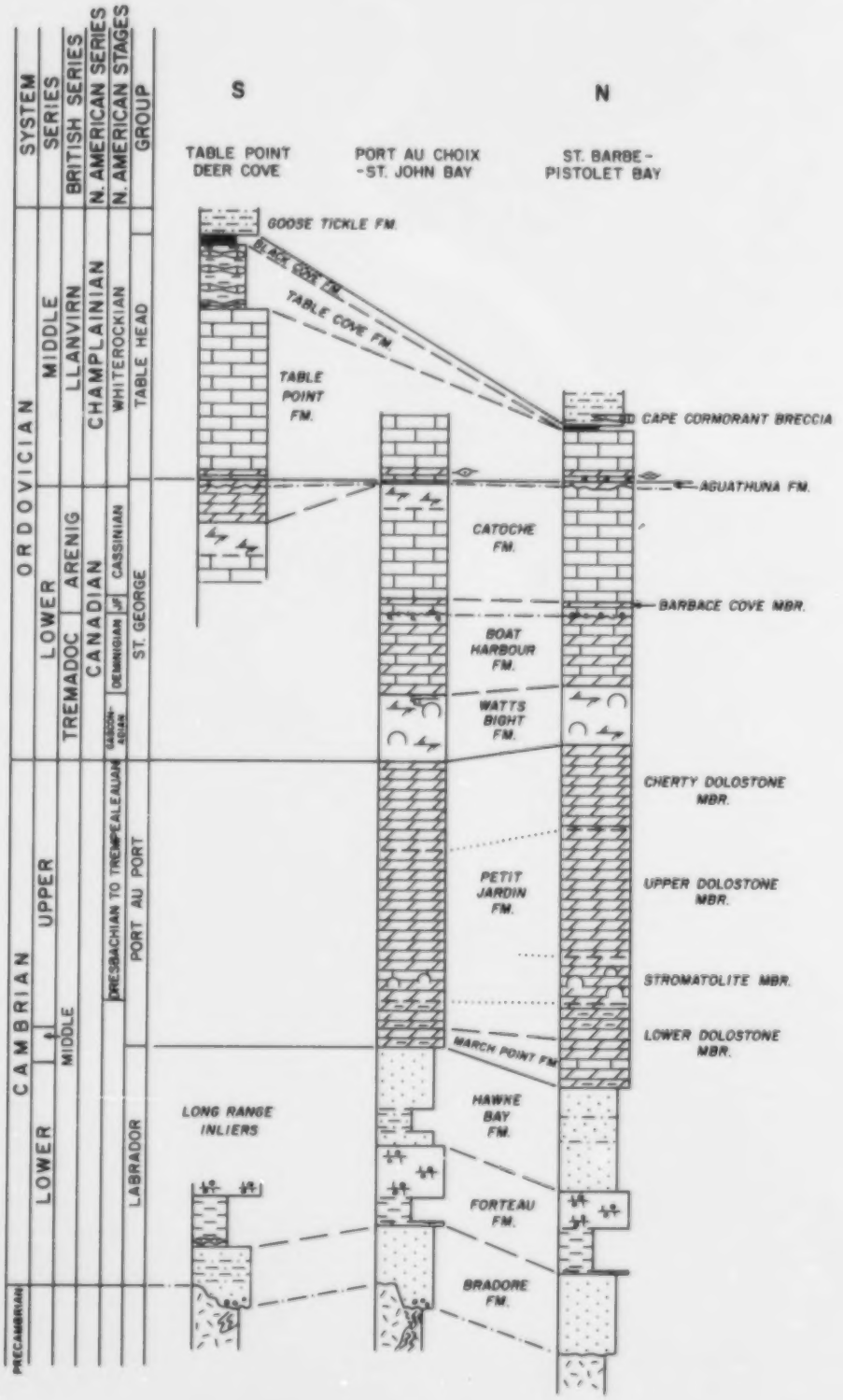
# GENERAL GEOLOGY AND STRATIGRAPHY

The rocks in the map area are part of autochthonous lower Paleozoic platformal strata that extend from Cape Norman, south to Portland Creek along the northwest side of the Great Northern Peninsula (Figure 1). The autochthon lies west of an uplifted fault block of Grenvillian basement rocks, which form the core of the Long Range Mountains. Together, the basement and autochthonous rocks form a part of the Humber tectono-stratigraphic zone of Williams (1978a). The autochthonous carbonate rocks are, generally, gently dipping except close to faults where they may be folded and steeply dipping to overturned. The faults, which dominantly trend northeast, break up the lateral continuity of the stratigraphy. Stratigraphic subdivision of the autochthonous rocks (Figure 2) follows currently accepted terminology and practice outlined by recent investigations (see Table 1).

## GRENVILLIAN BASEMENT ROCKS AND BASAL UNCONFORMITY

Basement-cover relationships occur within the map area. Basal rocks of the Labrador Group overlie Grenvillian basement rocks associated with a marked unconformity in a number of areas. Basement is exposed beneath the Labrador Group along the foot of the western scarp of the North Summit of the Highlands of St. John. Here, it forms a narrow inlier bounded to the west by the Ten Mile Lake fault, and extending 15 km from Greta Gulch to just south of Castors River. Mapping (in 1983) shows that this basement inlier is not continuous (Knight, 1983) with basement rocks previously mapped at the foot of Mount St. Margaret (Williams, 1967, 1978a; Snow and Knight, 1979). The two basement inliers are separated by a fault-bounded, downthrown block of the Forteau and Hawke Bay formations in the vicinity of Three Mile Pond and the south side of Castors River. The presence of the North Summit basement inlier was clearly illustrated in published cross sections of this part of the Highlands of St. John, by Johnson (1941) but was overlooked by subsequent workers such as Williams (1967, 1978a).

A number of gently westward-dipping Labrador Group outliers, sitting piggy-back upon uplifted basement of the Long Range Mountains, occurs on the western edge of the Torrent River map sheet. The basal unconformity can be located to within a few metres at several locations where it is usually concealed in an entrenched stream gully. Locally, it is cut by minor faults affecting both basement and cover. However, mapping and airphoto interpretation of the contact suggest the unconformity had marked topographic relief, south of Pikes Feeder Pond. At Black Stag Pond, the unconformity occurs at the water level. Immediately east, a


SYSTEM
SERIES
GROUP
ORDOVICIAN
CAMBRIAN
MIDDLE
LOWER
UPPER
BRITISH SERIES
N. AMERICAN SERIES
N. AMERICAN STAGES
TREMADOC
ARENIG
LLANVIRN
CANADIAN
CHAMPLAINIAN
WHITEROCKIAN
CASSINIAN
DEMINGIAN
GASCONADIAN
CRESBACHIAN TO TREMPEALEAUAN
TABLE HEAD
ST. GEORGE
PORT AU PORT
LABRADOR
PRECAMBRIAN
S
N
TABLE POINT DEER COVE
PORT AU CHOIX -ST. JOHN BAY
ST. BARBE - PISTOLET BAY
GOOSE TICKLE FM.
BLACK COVE FM.
TABLE COVE FM.
TABLE POINT FM.
CAPE CORMORANT BRECCIA
AGUATHUNA FM.
CATOCHE FM.
BARBACE COVE MBR.
BOAT HARBOUR FM.
WATTS BIGHT FM.
CHERTY DOLOSTONE MBR.
PETIT JARDIN FM.
UPPER DOLOSTONE MBR.
STROMATOLITE MBR.
LOWER DOLOSTONE MBR.
MARCH POINT FM.
HAWKE BAY FM.
FORTEAU FM.
BRADORE FM.
LONG RANGE INLIERS

round knob of granite rises 110 m above the pond but is not capped by sedimentary rocks. No faults apparently occur between the hill and the unconformity suggesting that the hill is an exhumed lower Paleozoic topograhic feature. Farther south, at the southern end of the same inlier (Grid reference, NTS 121/10, 5035/55995), the unconformity rises about 30 m over a granite hill. The hill is bounded by an intersecting set of lineaments that trend 103 and 123° and are truncated by the unconformity. Other lineaments and minor faults are abundant in the granite basement. They have variable trends; some of them stop at the unconformity but others cut both basement and cover, suggesting they postdate deposition of the lower Paleozoic succession.

Considerable relief upon the unconformity is supported by relationships on the Castors River map sheet at the north end of the Long Range massif, east of East Castor Pond. Here, two faults that trend 025 to 045° are interpreted to be of nearly contemporaneous age to the sediments. They root within the Precambrian basement 2 to 4 km southwest of the northeast-plunging Paleozoic unconformity. In the basement, northeast structural trends in gneisses that are intruded by quartz monzonites and granites (Bostock *et al.*, 1983) are truncated by the unconformity. The overlying Bradore Formation is offset by the fault that cuts the basement west of Beaver Brook Pond. However, the fault separates a hilly terrain to the southwest that is underlain by possibly as much as 650 m of Bradore sandstones (based upon an average dip of 10° and an outcrop width of approximately 3.8 km). Northeast of Beaver Brook and east of the fault, approximately 100 m of Bradore sandstones only, occur, (based upon a 5° dip, seen in strata on the western edge of the Roddickton map area, and upon an outcrop width of about 1.3 km). There is little displacement across this fault of the shale–limestone boundary within the Forteau Formation to the northeast. This suggests that the anomalous thickness of the Bradore Formation and the apparent major displacement to the northwest across the fault, is related to Eocambrian or Early Cambrian movements on the fault prior to, or simultaneous with, deposition of the Bradore Formation. Considerable relief is thus probable across this fault; a topographic high lying to the east. Bostock (*in* Bostock *et al.*, 1983) concluded that faulting took place in the area after the deposition of the Bateau Formation (late Precambrian) but before mafic dykes were emplaced and the Bradore Formation was laid down.

The western side of the Labrador Group outliers are cut off by the north-trending Lady Worcester Brook fault (LWB). Precambrian basement rocks and the unconformity are rarely exposed to the west of this fault. However, they do occur in a fault-bounded wedge, west of the fault 5 km north of Pikes Feeder Pond, at the northern margin of the Torrent River map area.

The basement rocks that directly underlie the Labrador Group in the Torrent River area consist of pink to red leucogranites that are dominantly equigranular, fine to coarse, locally porphyritic, megacrystic and pegmatitic. They are composed of quartz, pink K-feldspar, mostly microcline, oligoclase and accessory chlorite variably developed after biotite and magnetite. The granites are massive, and have an indistinct tectonic fabric seen only in one outcrop east of Little Sugar Loaf (NTS 121/15) and in the area, north of Pikes Feeder Pond. Here, the granites are also cut by a prominent set of northeast-trending (035°), southeastward-dipping (8°) joints. In the Beaver Brook area (Castors River map sheet, NTS 121/15), the granites are associated with banded quartzofeldspathic and hornblende–biotite–quartz gneisses (Bostock *et al.*, 1983). Rafts of banded quartzofeldspathic gneiss occur within the granite in a low hill 3 km north of Pikes Feeder Pond.

The unconformity was rarely examined due to cover in the areas mapped. The unaltered nature of the granite only 2 to 3 m below the ancient land surface, however, suggests that little or no regolith exists. However, Foley (1937) described 'Precambrian gneiss, much shattered, close to the unconformity', exposed in a narrow gulch, he called Contact Creek, just to the east of Pikes Feeder Pond. Nelson (1955) in his description at the same location (he called it Contact Brook) indicates that the Bradore Formation rests on highly weathered gneiss, the unconformity being fairly smooth having local, rounded, 15-cm-high irregularities.

Bostock (*in* Bostock *et al.*, 1983, page 33) describes 1.5 m of red-brown friable granitic regolith containing 60 percent weathered feldspar at the unconformity, presumably at the same locality. In the description, they locate the contact in a tributary that enters Torrent River from the north at the entrance to Eastern Blue Pond. Since the Torrent River and Eastern Blue Pond are on separate river systems, it is possible this locality is different to Contact Brook near Stag Pond. The regolith overlies leucocratic gneiss and contains weathered feldspars and disordered micas.

The unconformity at Contact Brook was re-examined. It is a planar sharp surface (Plate 2), dipping 9° west, parallel with overlying sediments. Beneath the unconformity, massive leucocratic gneiss (Bostock *in* Bostock *et al.*, 1983) appear unaltered but contain brown micaceous, ferruginous bands that penetrate for up to 25 m below the unconformity. Overlying the unconformity, brown, argillaceous, poorly sorted, fine-grained sandstones pass up into crudely stratified and crossbedded, medium- to very coarse-grained sandstones rich in heavy minerals. Although a regolith was probably developed below the unconformity, it was mostly reworked and eroded down to generally unaltered crystalline rock.

**Figure 2.** *Stratigraphy of lower Paleozoic autochthonous rocks in the map area, correlated with key sections of the Great Northern Peninsula; Table Point Section (Klappa* et al., *1980; Knight, 1977, 1978); St. Barbe section (Knight, 1977, 1986; Cumming, 1983); Jf–Jeffersonian.*

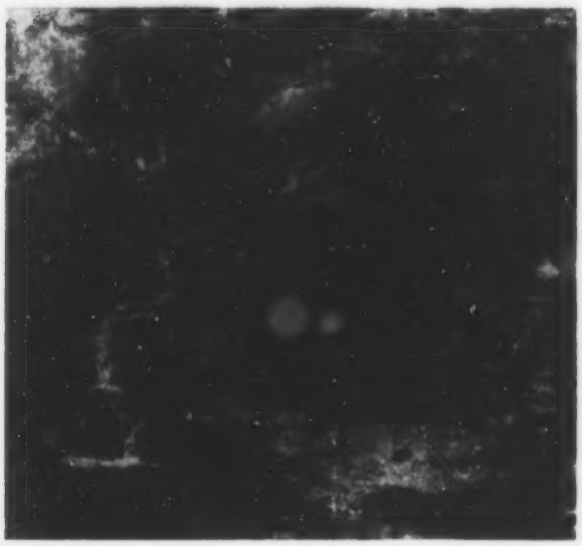


**Plate 2.** *Red sandstone of the Bradore Formation unconformably overlying apparently unweathered leucocratic gneiss. The contact (arrow) is sharp and planar; Black Stag Pond Brook, Torrent River map area.*

Weathered zones that penetrated deeper along micaceous or mafic bands in the crystalline rocks are the preserved remnant of the regolith. In Labrador, Hiscott *et al.* (1984) describe an undulating unconformity with the local presence of weathered regolith at the top of older gneisses.

# LOWER CAMBRIAN MIXED SILICICLASTICS AND CARBONATES

## Labrador Group

Siliciclastic and carbonate rocks of the Labrador Group overlie the Grenvillian basement rocks. Three formations occur in the group; a basal red arkose (Bradore Formation), a middle shale–limestone (Forteau Formation) and an upper white quartz arenite (Hawke Bay Formation).

The Labrador Group underlies the uplifted mountainous terrain of the Highlands of St. John and Mount St. Margaret. It also forms a group of outliers that sit piggy-back upon Grenvillian basement on the western edge of the Long Range Mountains to the east of the Lady Worcester Brook fault (LWB). West of this fault, the group underlies ridge and valley and marshy country between the Torrent River and Big East River systems. Hawke Bay sandstones underlie scattered areas near Western Brook Pond and west of LWB fault. The upper half of the group also outcrops at the head and north and south shores of Hawkes Bay. Overlying these sandstones is a black shale that forms the base of the late Middle Cambrian March Point Formation. As such, although the group is generally given a Early Cambrian age, it is quite likely that unfossiliferous quartzose sandstones at the top of the group span into the Middle Cambrian. This is based upon fossils that belong to the upper part of the *Bonnia–Olenellus* zone in the lower part of the Hawke Bay Formation, and recent biostratigraphic work on the Hawke Bay Formation near Canada Bay and Gros Morne by Knight and Boyce (1987; unpublished data, 1987). Generally, these fossiliferous beds in the lower Hawke Bay Formation are overlain by more than 80 m of unfossiliferous strata before the first fossils of Middle Cambrian age are encountered in the overlying March Point Formation. However, equivalent strata to this unfossiliferous upper Hawke Bay Formation in the Canada Bay and Gros Morne areas have yielded Middle Cambrian fossils. Palmer and James (1979) have proposed that the deposition of the Hawke Bay Formation reflects a major regressive event on the North American Craton and may include a disconformity of unknown magnitude.

### *Bradore Formation*

#### *Definition and Distribution*

The Bradore Formation, which is composed dominantly of red arkosic sandstones and forms the basal formation of the Labrador Group, rests unconformably upon Precambrian basement. This formation, which correlates with division A of the Potsdam Group (Logan, 1863), was first named and described by Schuchert and Dunbar (1934) at Cain's Ladder and along Frenchman's Brook in the Highlands of St. John. The formation was also studied by Woodard (1957) who divided it into two members, the Two Mile Pond and Cain's Humbug Brook members. Most of Woodard's descriptions are of strata exposed in valleys on the east side of the Highlands of St. John and not on the western scarp face. The members appear to be of very local significance and are difficult to map so that they are not utilized in this report.

The Bradore Formation has been mapped from the southern end of Mount St. Margaret (Castors River NTS 12I/15) to just southwest of Frenchman's Brook, where it is truncated against the Ten Mile Lake fault. North of this point, the formation forms the base of the steeply rising slope at the foot of the western scarp face of the Highlands of St. John. Good exposures of the formation can be seen east of the Ten Mile Lake fault in the bed and steep banks of Doctors Brook, at Cain's Ladder, Frenchman's Gulch, in tributaries that branch north off Doctors Brook and in the hillsides north and south of Greta Gulch and west of Squid Cove. The formation is also well exposed along the road that enters the shale quarry at the north end of Three Mile Pond.

The many outliers of Labrador Group that hug the western edge of the Long Range Mountains, east of LWB fault, contain fairly well-exposed rocks of the Bradore Formation. The outliers have previously been described by Foley (1937) and Nelson (1955).

West of the area, neither base nor top of the formation are exposed. On a tributary north of Doctors Brook, the first beds of Forteau Formation that were encountered just above the upper contact are composed of thick-bedded, massive, fossiliferous, pale-grey, rusty-weathering limestones. These

may be equivalent to the basal Devil's Cove limestone of Canada Bay (Knight and Saltman, 1980).

*Thickness*

Schuchert and Dunbar (1934) noted that the upper 45 m of the Bradore Formation are exposed at Frenchman's Brook but suggested that the total thickness was more likely 85 m by comparison to the section in southern Labrador. A structural cross-section at Mount St. Margaret suggests the Bradore Formation is between 110 and 150 m thick and is somewhat thicker than the 60 to 105 m section measured in southern Labrador by Hiscott *et al.* (1984). The formation is 122 m thick in a drillhole near Yankee Point, Flowers Cove on the St. Barbe coast (Cumming *in* Bostock *et al.*, 1983).

In the Long Range outliers, the Bradore Formation consists of approximately 70 to 90 m of strata. However, no upper contact is exposed and it has not been possible to measure a complete section of the formation. Nelson (1955, Table 1 and page 18) estimated the formation to be only 60 m thick. Woodard (1957) gave a thickness of 90 m for the formation; however, it is not clear how he arrived at that number because he combines two members whose interrelationship is not clear.

*Lithology*

Red and brown arkosic sandstones, granule to small pebble conglomerates, grey to pink glauconitic sandstones and minor grey shales compose the Bradore Formation. Two, possibly three, different successions occur in the formation from west to east. In the west of the Highlands of St. John, the succession is dominated by red, frequently pebbly and gritty, arkosic sandstones associated with minor quartz and feldspar pebble–conglomerate and grey glauconitic sandstones; white to red, *Skolithus*-bearing quartzose sandstones occur toward the top of the formation. The grey sandstones, which are only a few metres thick, appear to lie toward the base of the incompletely exposed section of the formation on Doctors Brook. They have not been seen in the north near Mount St. Margaret.

In the Long Range outliers, however, the succession consists of approximately 9 m (Foley, 1937) of brown-red, pebbly sandstone and small pebble conglomerate, overlain by approximately 50 m of grey and pink, glauconitic sandstone, siltstone and grey shale and is overlain by nearly 30 m of red and white sandstone.

On the east side of the Highlands of St. John overlooking Big East River, Woodard (1957) placed 12 to 15 m of grey, glauconitic sandstone in a lower member (Two Mile Pond Member) at the base of the formation. These beds are overlain by the Cain's Humbug Brook Member, an upper member composed mostly of red sandstones and minor pebble beds. This succession in the Big East River valley has not been substantiated. However, the grey facies forms an important part of the formation in the hills north of Beaver Brook and near East Castor Pond on the Castors River map sheet.

The red beds of the Bradore Formation on the western side of the Highlands of St. John are characterized by dark red to purplish-red, abundant pink detrital feldspar, friable weathering and fine sand- to granule-sized detritus. The sandstones are generally thick bedded, containing abundant scours and trough cross-sets up to 60 cm thick and 1 m long; beds up to 10 cm thick of planar thin stratification and lamination also occur. Heavy minerals concentrated in black laminae are common. Scour-based, small-pebble conglomerates up to 15 cm thick, composed essentially of white quartz and pink feldspar also occur in the red sandstone. The conglomerates are friable with a heavy mineral-rich sandy matrix. Ferruginous liesegang rings are common. Crossbeds in the sandstones appear to give an eastward paleoflow direction.

The grey sandstones on Doctors Brook are dominantly very fine to fine grained and consist of massively weathered 5 cm beds or medium to thick beds of planar thin stratification and lamination. Scattered quartz pebbles and pebble layers associated with shallow scours lie within the thin stratification. At the base of the grey sandstones and resting upon red, pebbly and granular arkose is a bed of grey grit, which is rich in shaly intraclasts and overlain by a 25 to 40 cm bed of structureless, green-grey sandy siltstone. The latter was reported first by the author (Knight, 1983) as a possible diabase sill.

Within the Long Range outliers, the basal red beds are dominantly poorly sorted, friable, pebbly and granular, very coarse sandstones, and granule and small pebble conglomerates. The matrices of the arkosic sandstones are rich in black heavy minerals, which also compose laminae locally up to 0.5 cm thick. White quartz, pink feldspar and granite compose the angular to rounded, 1-cm diameter pebbles of the facies. Cross-stratification, 20 to 30 cm thick, having straight foresets and planar scour bases, dominates the thick beds that compose the facies; some crude planar stratification also occurs. No bedding-plane exposure of the crossbeds has been seen but the style of foreset and bounding surfaces suggest many are tabular planar cross-sets.

The overlying grey sandstone facies commences with a rusty weathering, black, very fine- to fine-grained, glauconitic sandstone approximately 1 m thick. Beds, 20 to 40 cm thick, are composed of platy, horizontal planar stratification and small crossbeds. The overlying strata of the grey sandstone facies is not well exposed. Scattered outcrops and loose blocks suggest the facies is composed mainly of grey and pink, fine- to very fine-grained sandstones and coarse siltstones that are glauconitic. Bedding is mostly platy, with internal planar lamination, ripple crosslamination and scarce burrows (Plate 3). Crossbeds, 15 cm thick, and beds of pebbly, massive, medium-grained sandstone also occur within the finer rock types. Planar-bedded, well-sorted, white to pink, fine- to medium-grained, arkosic sandstones containing *Skolithus linearis* occur toward the top of the grey sandstone facies in the outlier, southeast of Pikes Feeder Pond. Grey shale partings and beds up to 20 cm thick are locally common.

**Plate 3.** *Thinly stratified, parallel-laminated and crosslaminated, grey, very fine-grained, micaceous sandstone and shale of the grey facies, Bradore Formation, 'Ballocky Hill', Torrent River map area.*

The upper red bed unit is poorly exposed. It consists of thick beds of brown-red, poorly sorted, commonly pebbly and gritty, very coarse- to fine-grained, arkosic sandstone. Sedimentary structures include 20- to 30-cm-thick trough cross-stratification and gently inclined planar stratification. Nelson (1955) describes green-grey, glauconitic sandstone up to 5 m thick along Black Stag Pond Brook. The grey sandstone facies is intercalated in the red beds just below the upper contact of the Bradore Formation.

*Petrology*

The red sandstones of the Bradore Formation consist of arkose and subarkose composed of quartz, microcline, microcline–perthite, some plagioclase and rare muscovite. The matrix is composed of sericite and chlorite; it reachs 5 to 10 percent in poorly to moderately well-sorted sandstones (Beard and Weyl, 1973). In such rocks, grains are angular to subrounded and are extensively fractured. The fractures are infilled by the sericite matrix, suggesting that the clays may be the product of diagenesis or squeezed in from the matrix and later recrystallised. Higher in the section, just below the Forteau Formation, medium- to coarse-grained sandstones are better sorted and are indurated by the presence of silica cements. Although quartz and (locally) alkali feldspar have overgrown sand grains, a dusty line of hematite indicates that the grains were well rounded.

Common quartz in the red sandstones is typically derived from plutonic and vein quartz that is rich in vacuole trails and inclusions having straight to slightly undulose extinction. Composite quartz is not common and is mostly of similar type although some grains of metamorphic origin showing equi-granoblastic texture and extreme crystal elongation occur. The feldspars are mostly fresh with some alteration of one perthitic phase. Some reddened dusty orthoclases also occur and these may show secondary alteration. Heavy minerals are dominated by magnetite, zircon and sphene and rare grains of green tourmaline. Leucoxene, hematite and limonite have replaced the magnetite and leucoxene rims, and mask much of the sphene. Heavy minerals are both scattered in the arkoses and concentrated as millimetre thick laminae. Minor glauconite was reported by Woodard (1957) in the red sandstones but none was noted by Smit (1971) or the author.

The grey sandstones of the formation are very fine to fine grained and moderately well sorted. They consist of angular to rounded grains of quartz, microcline, perthite plus muscovite and biotite micas set in a matrix of chlorite and clay minerals. They are cemented in some beds by patchy silica and carbonate cements, the carbonate replacing feldspars. Heavy minerals are rare except in discrete laminations and like the red sandstones include magnetite, sphene and zircon. Both magnetite and sphene are commonly replaced by hematite and leucoxene. Scattered in the grey sandstones are irregular to rounded grains of glauconite that constitute 1 percent of the rock. Woodard (1957, page 12) described 15 to 35 percent glauconite in the grey sandstones of his Two Mile Pond Member. He showed an inverse quantitative relationship between the presence of glauconite and sericite–muscovite in the sandstones. The grit at the base of the grey sandstones consists of elongate rip-up intraclasts and subrounded to rounded quartz granules set in a medium sandstone matrix. The intraclasts consist of a brown, carbonaceous, very fine-grained sandstone and shale. The granules are composed of 'common' quartz, polycrystalline plutonic quartz, microcline–perthite (some enclosing quartz crystals), and granite, which may contain brown biotite. The medium-grained-sandstone matrix contains a typical Bradore sandstone mineral suite set in a chloritic matrix. Scattered glauconite grains occur in the sandstone.

*Paleontology*

Only trace fossils are known in the Bradore Formation. *Skolithus linearis* (Plate 4) occurs in red and white, well-sorted sandstones of the upper part of the Bradore Formation along the quarry access road at Three Mile Pond. No *Skolithus* has been described at Frenchman's Brook (Schuchert and Dunbar, 1934) although Smit (1971) noted the trace fossil in float, at this locality. *Skolithus* is apparently abundant in red beds of the east side of the Highlands of St. John (Woodard, 1957). It was also noted by the author in grey and pink micaceous sandstone on a hilltop on the northernmost Long Range outlier on the Torrent River map sheet.

*Depositional Environment*

The rocks of the Bradore Formation were laid down in both fluviatile and shallow-marine settings. The presence of *Skolithus*, grey glauconitic siliciclastics and well-sorted quartzose and arkosic sandstones in the upper part of the

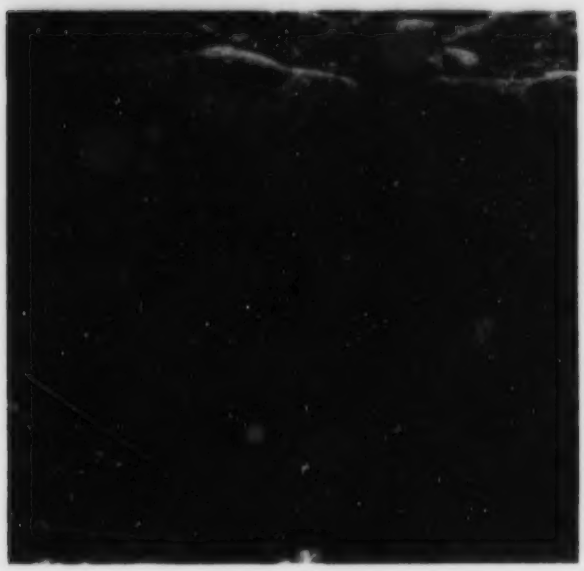


**Plate 4.** Skolithus linearis *in cross-section. Red sandstone bed of the Bradore Formation, Mount St. Margaret.*

Bradore Formation has prompted several workers (Smit, 1971; Swett and Smit, 1972a; Waring, 1975; James and Hiscott, 1982) to interpret some, if not all, of the Bradore Formation as a marine strandline sequence. However, the red aspect and poorly sorted nature of most of the formation in the west suggest much of it was deposited subaerially. The poorly sorted, argillaceous granular red sands of the lower part of the Highlands of St. John succession are dominated by eastward-directed trough crossbeds that suggest they were laid down in a fluvial regime. The lack of fine red interbeds, the predominance of scours and trough crossbeds and the coarse sandy to pebbly nature of these unsorted siliciclastics suggest they were laid down by sandy and gravelly braided streams.

A similar interpretation has been proposed by Knight and Saltman (1980) for red sandstones of the lower part of the Bradore Formation in Canada Bay and by James and Hiscott (1982) and Hiscott *et al.* (1984) for the redbeds of the Blanc Sablon Member of southern Labrador. A braided fluvial depositional setting is probable for the lower and upper red bed sequences of the Long Range outliers. Here, the basal granular and pebbly red arkosic sandstones, which are characterized by planar cross-stratification and sharp planar-bounding surfaces, were probably laid down in transverse bars of a gravelly, braided stream system (Miall, 1977; Rust, 1978).

Grey, glauconitic sandstones and *Skolithus*-bearing, well-sorted sandstones were laid down under marine conditions. In the east, marine incursion drowned the floodplain in the early history of the formation so that the grey sandstones buried the basal red beds of that area. During the deposition of a considerable proportion of the remaining part of the formation, marine conditions prevailed in the east. However, the sea retreated and fluvial sands prograded eastward into the area of the outliers as deposition of the formation came to an end. The absence of *Skolithus* in these younger red beds suggests that river-laid sands overwhelmed transgression in this area. Probable partly contemporaneous red beds in southern Labrador contain abundant *Skolithus*, which suggested to Hiscott *et al.* (1984) that fluvial sands along the shoreline were biologically reworked in distributory-mouth estuaries (their Crow Head Member). In the west of the map area, marine conditions persisted only briefly during the early history of the formation before riverlain sands re-established themselves.

The grey facies, which is poorly exposed, consists mostly of intercalated glauconitic sandstones and thin grey shales and siltstones. High argillaceous and glauconitic content of the sands and dominantly small-scale sedimentary structures and apparent lack of subaerial features and the presence of *Skolithus* suggest these intercalated sediments were deposited sublittorally. Nonetheless, because the red sandstone of the Bradore Formation were laid down on a sandy alluvial or coastal plain, the grey sandstone may represent an estuarine or deltaic facies.

The basal beds of grey sandstone facies in the outliers and grey sandstones along Doctors Brook, both characterized by good sorting, fine grain size, dominantly horizontal planar lamination and compositional laminae of heavy minerals, may be shoreface beach deposits. The granular sand body at the base of the Doctors Brook succession possibly represents reworking of the underlying fluvial deposits as the sandy alluvial plain was flooded by the sea. The presence of grey, carbonaceous shale and muddy sand intraclasts in the deposit suggest that the first deposits of the transgression may also have been reworked during marine onlap.

Although non-marine sedimentation prevailed in the west and was re-established high in the formation in the east of the map area, the Early Cambrian sea again flooded the east and north of the map area during the last depositional stage of the formation. The grey sandstone is intercalated with red sandstone beds in the east. Red and white, fine quartzose and arkosic sandstones form the top of the formation at Mount St. Margaret. These sandstones are well sorted, and contain rounded sand grains and the problematic trace fossil *Skolithus linearis*. They were probably deposited in a high energy, sandy shoreline setting.

### *Forteau Formation*

#### *Definition and Distribution*

A succession of interbedded shales, limestones and lesser sandstones comprise the Forteau Formation. The formation, originally Richardson's division B (Logan, 1863), was named and first described by Schuchert and Dunbar (1934) in southern Labrador and on the western face of the Highlands of St. John. The formation forms the middle levels of the western face of the Highlands and of Mount St. Margaret. The upper beds of the formation are also exposed at the head of Hawkes Bay and the formation continues inland to underlie the area between the Torrent River fault and Big East River.

The formation also caps the main Long Range outliers south of Pikes Feeder Pond. During the present study, the formation was not studied in great detail and the following description uses existing literature to supplement details provided by the author.

The Forteau Formation probably conformably overlies the Bradore Formation as it does elsewhere on the Great Northern Peninsula (Smyth, 1973; Knight and Saltman, 1980) and southern Labrador (Schuchert and Dunbar, 1934; James and Kobluk, 1978; James and Hiscott, 1982). The basal contact is placed at the base of a red and grey, granular, thick-bedded, *Salterella*-bearing limestone (Schuchert and Dunbar, 1934; Smit, 1971, page 184; James and Kobluk, 1978). This limestone is probably equivalent of the Devil's Cove limestone of Canada Bay (Betz, 1939; Smyth, 1973; Knight and Saltman, 1980) and a basal red dolomite that occurs at the base of the formation in the type area of southern Labrador (Schuchert and Dunbar, 1934; Smit 1971; James and Kobluk, 1978). Schuchert and Dunbar (1934) show the contact exposed in the section on Frenchman's Brook, and Nelson (1955, page 12, 13) describes a conformable basal contact on Black Stag Pond Brook. Here, 5 m of pink and grey, shaly dolomitic limestone, limestone and dolostone sit upon red conglomerate of the Bradore Formation; neither locality was observed during this study. The upper contact is placed at the base of the first bed of white quartz arenite belonging to the Hawke Bay Formation; the contact is exposed on the south shore of Hawkes Bay, just 0.6 km from Hawkes Bay itself.

*Thickness*

Schuchert and Dunbar (1934) give the thickness of the Forteau Formation as 115 m at Frenchman's Brook; Smit (1971) presents a thickness of 149 m at the same locality.

*Lithology*

The Forteau Formation is composed principally of grey and black shales, bedded arenaceous, fossiliferous and oolitic limestones, dolostones, archaeocyathid-bearing limestones and calcareous siltstones and sandstones (Schuchert and Dunbar, 1934; Woodard, 1957; Smit, 1971; James and Kobluk, 1978; James and Hiscott, 1982). The succession is divisible into three parts, a basal carbonate, a middle, dominantly shale succession, which is intercalated with thin beds of sandstone and carbonate, and an upper succession composed of grainy limestone, sandstone containing minor shale and archaeocyathid limestone.

*a) Basal Carbonate Member.* Six metres of red to grey, thickly bedded, fossiliferous, crystalline dolostone and limestone form the base of the formation. These carbonates are *Salterella*- and trilobite-rich, skeletal packstones and, locally, grainstones. They characteristically display lumpy nodular bedding and shale partings. The skeletal grains in the grainy limestones are closely packed with scattered crinoid elements and rare grains of phosphate and the cellular algae *Bija*. Many fragments are coated by fibrous radiating cement fringes and crinoid grains are extensively replaced by micrite and in some instances, glauconite. Leaching of some skeletal grains has occurred and the space filled by clear blocky spar, which also cements other porosity. Silty to skeletal wackestone and microspar fill most of the area between grains.

*b) Middle Shale Member.* Shale, having thin limestone and sandstone interbeds, comprises a section 30+ m thick at Frenchman's Brook (Schuchert and Dunbar, 1934), above the basal limestones. These beds are very well exposed in a quarry on the western slopes of Mount St. Margaret (Plate 5), where they are about 38 m thick. In the Long Range outliers, the thicknesses of the shale-dominated sequence calculated from outcrop distributions in the area is greater, and may be at least an order of magnitude more than in the Highlands of St. John. Locally, in the Highlands of St. John, the shale section contains nodular limestones. The shale member in the west is composed of brown and greenish-purple weathering, black to purplish-grey, manganiferous shale approximately 25 m thick, overlain by approximately 13 m of intercalated grey shale–mudstone and brown-weathering, grey calcareous sandstone and silty limestone. The manganiferous shale is potassium-rich (Stevens and Knight, 1974; Swett and Smit, 1972b). In the lower 7 m, the shale is extensively bioturbated by *Planolites*. In the overlying 18 m, it contains abundant olenellid trilobites, which locally are concentrated in densely fossil-rich beds. Calcareous concretions and carbonate beds, 4 to 15 cm thick, of brown-weathering, grey and black skeletal packstone composed of trilobite and *Salterella* fragments also occur. Within the beds, the sedimentary fabric is disorganized so that the skeletal grains are swirled chaotically throughout the matrix and shale partings are broken and incorporated in the fabric.

**Plate 5.** *The lower shale member of the Forteau Formation, Mount St. Margaret quarry. The upper limestone member begins at the top of the face.*

Bioturbation is observable in some beds but absent in others. Small burrows (possible borings) are concentrated at several levels within the shale section; the burrows rarely penetrate more than 2 cm of sediment below a bedding plane.

Shale and calcareous sandstones are interbedded at 10 to 30 cm intervals in the upper part of the shale section. The sandstones are brown weathered, calcareous and very fine grained. Bases and tops of beds are planar on a large scale although on the local scale the basal contacts are irregular because of small-scale erosion, abundance of load casts and ichnofossils. Tops of beds are also rough due to bioturbation but locally display small, symmetrical ripple marks. The bioturbation has mostly destroyed internal structure. Locally, however, structures are preserved that show the beds were originally composed of ripple crosslamination, and planar and wavy lamination having common shale flaser and drapes. Ichnofossils (Plate 6) include burrow forms such as *Teichichnus*, *Chondrites*, *Cylindrichnus*, *Planolites* and a broad form of *Arenicolites*, and a small *Rusophycus* resting trace. Many of the tubular burrows are filled by dark shale only, but others are filled by interlaminated sand and mud suggesting possible multiple burrowing. The dark-grey shales and mudstones that are intercalated with the sandstones contain laminae and thin beds of brown-weathering, laminated siltstone. Burrows preserved by sand fill, mainly *Planolites*, riddle some of the mudstones layers.

*c) Upper Limestone Member.* The shales exposed in the Mount St. Margaret quarry are overlain by bedded, oolitic and skeletal calcarenites and archaeocyathid bioherms. A 35 cm bed of intraclastic rudstone and grainstone forms the base of the member. The rudstone consists of tabular fragments of laminated and crosslaminated dolostone and siltstone and archaeocyathid clasts set in a skeletal grainstone matrix. *Salterella*, inarticulate brachiopods, trilobites and black phosphatic grains make up the grainstone. Immediately above the grainstone bed, 1-m-high by 3-m-wide bioherms, spaced at 4 to 6 m apart, are surrounded by shales and thin, laminated and rippled, very fine-grained sandstones. Crossbedded grainstones and archaeocyathid bioherms overlie this basal interval of build-ups and are in turn overlain by black oolitic limestones, having some intercalated grey sandstones and shale.

*Archeocyathid Bioherms.* The biohermal limestones are rusty to buff weathering, grey, brown and pink, and consist of a variety of archeoyathid reef builders set in a dense, micritic matrix; *Metaldetes profundus* is most abundant and *Archaeocyathus atlanticus* Billings has also been noted at Mount St. Margaret. Cups and sticks are common, forming communities and scattered elements within skeletal packstones. Near the top of the biohermal section, in a red to pink zone that outcrops on the road that passes east of and behind Mount St. Margaret quarry, the reef is dominantly composed of arched sheets of *Retilamina amourensis* and some sticks of *Archaeocyathus atlanticus*. Encrusting algae and interstitial mud and cement fill the inter-skeletal spaces in the build-up.

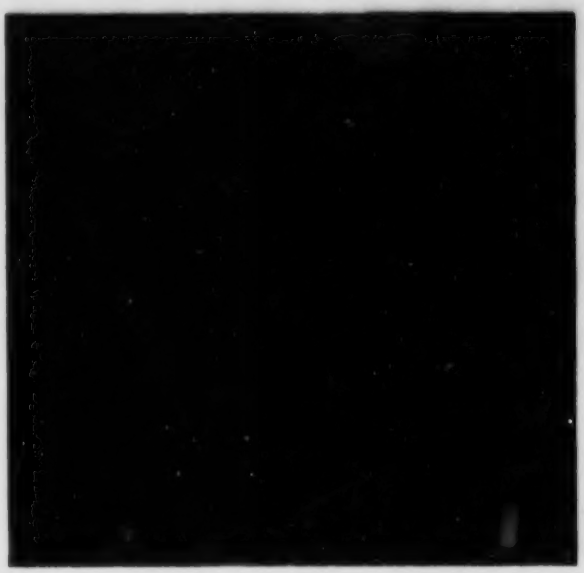


**Plate 6.** *Ichnofossils including resting traces and worm tubes on the base of a sandstone from the shale member, Forteau Formation, Mount St. Margaret quarry.*

In the Highlands of St. John, the biohermal limestones are exposed in several streams on the north side of the North Summit, and in the hills west and north of East Castor Pond (Castors River map sheet). They are also exposed at Frenchman's Brook (N. James, personal communication, 1982), and 1.9 km to the southwest at the foot of the scarp of the Highlands of St. John (NTS 121/14). At this locality, floatstone (Embry and Klovan, 1971), composed of archaeocyathid fragments set in a silty, skeletal wackestone and packstone matrix occurs, indicating derivation from a nearby biohermal build-up. Archaeocyathid fragments include *Retilamina* and *Metaldetes profundus*. The fragments are sometimes encrusted by layers of *Girvanella*, which also locally penetrate the fragments. Fronds, pendants and clustered masses of *Renalcis* and *Renalcis*-like calcareous algae (Kobluk and James, 1979) also encrust the framework builders. The depositional history within intraparticle space in the archaeocyathid fragments is complex and includes sediment-fills and cements that predate and postdate erosion and deposition. Early cements within the archaeocyathids include fringing druses of blocky to radiating blade-like microspar. These are overlain by a radial fibrous mosaic (Bathurst, 1975) and coarse blocky spar cements. The remaining space is filled by 10 μm microspar. Spaces within the fragments were also filled by skeletal wackestone and silty wackestone following deposition.

Numerous smaller carbonate grains are associated with the larger clasts in the floatstone. They include abundant trilobite and crinoidal particles as well as *Salterella*, brachiopods, the encrusting organism *Archaeotrypa*, some ooid grains and intraclasts composed of crinoid–ooid wackestone. Many of the grains show the effects of diagenesis. Leaching of skeletal fragments and filling of molds by blocky

spar occurred. Crinoid fragments are commonly enclosed by a micrite envelope with evidence of algal borings, up to 100 μm into the surface of the grains. Siliciclastic silt is widespread in the matrices and locally very abundant; minor glauconite also occurs. Late diagenetic dolomite of 500-μm-crystal size locally replaces the matrix of the floatstone.

A newly discovered archaeocyathid bioherm and intercalated grainstone occurs at the northwest end of Long Steady, Torrent River (Plate 7). The carbonate sits upon and intertongues with 1.4 m of 10 to 30 cm beds of very fine-grained, grey sandstone with shale flasers. The sandstones are laminated and crosslaminated and sparsely bioturbated. Yellow-weathering, dolomitic limestones, 0.2 to 1.5 m thick, rest upon the sandstones. The limestones are very coarse-grained grainstones composed of skeletal remains derived from the build-ups. Stylolitic clay seams are common in the grainstone, which is composed of crude, uneven, flat to somewhat lumpy thin stratification; some cross-stratification also occurs. The thickest development of grainstone (1.5 m thick) passes northeastward over a few metres into the very fine-grained grey sandstones, so that only 20 cm of grainstone separates the siliciclastics from the first bioherm at the northeast end of the exposure. The bioherms began as isolated patches 20 to 30 cm across, each expanding upward to coalesce into a massive biohermal complex. Internally, the reefs consist of clusters of 1 cm diameter sticks and more robust build-ups of sheet-like archaeocyathids. These are associated with *Metaldetes profundus*, calcareous algae and interskeletal sedimentary fills and cements. The top of the bioherm is not exposed but the complex is probably no thicker than 1 to 2 m. Nearby outcrops show that it is overlain directly by a crossbedded, dolomitic, oolitic sandstone, which is spectacularly exposed at the fish ladder on Torrent River. Here, the bioherm, which is deformed by the Torrent River fault, is exposed beneath the sandstone in the opposite river bank.

*Grainstones Associated with Bioherms.* Pink, well-sorted grainstones are intercalated with the red-sheeted bioherms. The very coarse-grained grainstones are composed of platy archaeocyathid particles that are imbricated; some larger fragments of archaeocyathid occur in the grainstones. Crossbedding occurs in pebbly, skeletal grainstones that contain clasts of reef detritus associated with a grey bioherm near the radio tower on Mount St. Margaret.

*Calcareous Sandstones and Arenaceous Limestone.* Above the archaeocyathid-bearing limestones, the succession is dominated by calcareous sandstone and arenaceous and argillaceous limestone. The calcareous sandstone rests upon the archeocyathid limestones in the area of Hawkes Bay and is well exposed along the north bank of Torrent River, Long Steady and Western Brook Pond, where it is overlain by black oolitic limestone. However, the calcareous sandstone has not been found in the area of Mount St. Margaret. Here grey, crossbedded, skeletal lime grainstones, similar to those already noted with the bioherms, are overlain by black oolitic limestone. At Frenchman's Brook, Schuchert and Dunbar (1934) describe 35 m of thinly bedded arenaceous limestone

**Plate 7.** *Archeocyathid bioherms overlying crosslaminated lime grainstone, Forteau Formation, Torrent River.*

(their Units 8 and 9, page 21) overlying archaeocyathid limestone and overlain by dark bluish-grey limestone that is clearly the oolitic limestone of this report. On the Bellburns map sheet in roadside exposures that occur east of Lady Worcester Brook fault, interbedded shale and very fine sandstone directly underlie the black oolitic limestone. These are similar and hence possibly equivalent to the upper parts of the calcareous sandstone seen in the Long Steady area. This interval in the formation, clearly contains a laterally variable group of lithofacies.

The arenaceous limestone of the Frenchman's Brook area, as described by Schuchert and Dunbar (1934), are thinly bedded along with shale partings in the lower 21 m. Cross-stratification is ubiquitous in the overlying 14 m. This upper unit may be similar to the widely distributed calcareous sandstones of the Torrent River area. These are white, very fine- to medium-grained, well-sorted, quartzose sandstone and buff- to brown-weathering, sandy, oolitic grainstones. The composition of the sandstone varies within the cross-stratification. Quartzose sandstone forms millimetre- to centimetre-thick laminae and layers parallel to foresets and scours within the calcareous sandstones. Carbonate-coated sand grains and ooids occur in the more calcareous laminae. Trough cross-stratification, 5 to 15 cm thick, up to a metre wide and several metres in length, is the major sedimentary

structure (Plate 8). Elliptical scours in cross-section are seen in longitudinal section to be long, planar, generally smooth features that locally are irregular or climb gently upward over the eroded backs of sets. Cross-stratified units appear to wedge-out downcurrent, partly because of erosion. Reactivation surfaces are common. Current directions of crossbeds are mostly to the southwest but also reverse to the northeast and rarely trend to the northwest. Larger crossbeds associated with some units of planar lamination occur toward the top of the sandstone.

**Plate 8.** *Crossbedded, oolitic sandstone, Forteau Formation, Torrent River.*

Upward, the sandstone becomes very fine grained ranging down to coarse siltstone. The sandstone consists of beds 10 to 30 cm thick composed of planar and crosslamination with minor crossbeds. It is intercalated with 10 to 30 cm beds of interbedded thin shale and wavy, crosslaminated, very fine-grained sandstone. Lenses and beds of grey, very coarse-grained, skeletal lime grainstone intercalate in these uppermost siliciclastic rocks. The grainstones are grey, rich in *Salterella* fragments, slightly bioturbated and, locally contain lenses of laminated siltstone. Similar interbedded shales and sandstones along the Mooney Block access road on the Bellburns map sheet include simple vertical burrows and *Arenicolites*.

*Oolitic Lime Grainstone.* The calcareous sandstone is overlain by approximately 23 m (Schuchert and Dunbar, 1934) of grainy limestone. This is dominantly black oolitic limestone having grey, skeletal grainstone developed at the base of the unit. The grainstone is composed of trilobite fragments and *Salterella*. It is commonly wavy to flat, thinly stratified with lenses and flaser of very finely laminated dolostone. Minor bioturbation, some crossbeds and rip-up clasts of dolostones also occur in the grainstone.

Throughout the map area, the black limestone is skeletal, oolitic lime grainstone. It is composed of very fine- to fine-grained ooids with coarser layers containing oncolites and intraclasts. The grainstone is generally thick bedded, and massive. Lenses, layers and drapes of dolostone, which are either structureless or laminated and crosslaminated, also occur. Sedimentary structures in oolitic limestone consist of wavy to planar thin bedding and small-scale cross-stratification, which in some instances comprises the thin beds. Large cross-stratification also occurs; it frequently displays herringbone structure typical of bimodal current directions. Intraclastic floatstone and rudstone form scour-based beds up to 20 cm thick in the grainstones. The commonest intraclasts, some as large as 10 by 2 cm, consist of cemented ooid grainstone. However, in other grainstones, the oolitic sand is interlayered with rudite composed essentially of dolostone intraclasts.

Oncolite-rich beds, displaying wavy planar stratification and cross-stratification, range through the oolitic grainstone section although Schuchert and Dunbar (1934) suggested that they are confined only to the upper 4 m of the Frenchman's Cove section. This bed, which occurs approximately 15 m from the top of the formation was called the 'button alga bed' by Schuchert and Dunbar (1934). It is well exposed beneath the Route 73 road-bridge over the Torrent River, along the foreshore at Hawkes Bay and in a roadcut (Route 73) near the mouth of Little East River. The same bed also occurs near the top of the Frenchman's Brook section (Schuchert and Dunbar, 1934). The 1 to 2 cm diameter oncolites are mostly yellow weathering and display dark-coloured, fine concentric laminae. Simple- to U-shaped burrows are distributed irregularly through the grainstone. In thin sections, ooids are generally poorly preserved. However, concentrically laminated cortices are present. Both radial and concentric fabrics are described by James and Klappa (1983).

*Shales and Calcareous Sandstone.* Above the black oolitic limestone on Frenchman's Brook, Schuchert and Dunbar (1934) show a *Salterella*-bearing shale that is 12 m thick. This same interval on the south shore of Hawkes Bay, and in the southeast corner of the map area, however, contains rusty weathering, grey calcareous sandstones interbedded with grey shales, which contain fragments of olenellid trilobites. The sandstones are well bedded, internally massive and contain abundant trace fossils that include *Arenicolites*, *Teichichnus* and simple burrows. Inarticulate brachiopods also occur in the beds. The sandstones contain glauconite(?), as well as skeletal grains and immediately underlie the white quartz arenites of the Hawkes Bay Formation (Knight, 1977).

### *Paleontology and Age*

Fossils have been recovered from the black shales at the base of the formation and from the grainy limestones toward the top. The shales contain the trilobites *Olenellus thompsoni* Hall (Billings, 1865; Woodard, 1957) and *Olenellus (=Paedumias) transitan* Walcott (Whittington and Kindle, 1969; Boyce *in* Stouge and Boyce, 1983). The trilobites *Bonnia* and *Olenellus*, including unnamed inarticulate brachiopods,

were also noted associated along with the archaeocyathid bioherms at Mount St. Margaret by Whittington and Kindle (1969). The grey and black grainstones and the immediately underlying interbedded shales and fine sandstone at the top of the formation have yielded inarticulate brachiopods, the problematic mollusc *Salterella* as well as the trilobites *Wanneria logani* Walcott, *Olenellus (= Paedumis) transitans* Walcott, *O. lapworthi* Peach and Horne, *O. brevoculus* Resser and Howell, *Bonnia senecta* and *Kootenia* sp. nova. A rich fauna occurs near Hawkes Bay in a roadstone quarry at the junction of Route 73 and the road to the fish ladder. *Olenellus brevoculus* Resser and Howell (Boyce *in* Stouge and Boyce, 1983) occur in shales and grey sandstones at the very top of the formation along the south shore of Hawkes Bay. The fauna, as a whole, belongs to the *Bonnia–Olenellus* Zone of Fritz (1972) and together with the archaeocyathids suggests a late Early Cambrian age (James and Kobluk, 1978).

*Depositional Environment*

The Forteau Formation contains deposits of a mixed terrigeneous–carbonate shelf that developed extensively in northwest Newfoundland and southern Labrador as marine transgression prevailed in the Early Cambrian and drowned strandline sands of the Bradore Formation. Fine terrigeneous detritus reached the shelf but the importance of 1) clean carbonates, 2) bioherms, and 3) a rich assemblage of skeletal organisms, confirms that the warm shelf seas were fairly clean. In southern Labrador, similar strata were interpreted by James and Kobluk (1978) to have formed on a shallow water, subtidal, open shelf that hosted, at times, numerous metazoan bioherms.

In the map area, the formation commenced with the deposition of a shaly, fossiliferous wackestone and packstone that rests upon granular red dolostone. The abundance of intact *Salterella*, which is believed to be a shallow-water benthonic organism (Reinhardt and Wall, 1975; Yochelson, 1977), the lumpy to nodular bedding and shale partings, suggest that this basal lumpy bedded limestone was deposited in a shallow, subtidal shelf setting that was quickly established following deposition of the red granular dolostone. In Labrador, the red dolostone is a grainstone that exhibits cross-stratification (James and Kobluk, 1978) and is presumably similar to the red dolomite of the map area. James and Kobluk (1978) interpret the dolostone as a shoreline carbonate sand body. The carbonates then clearly reflect transgression upon the platform with rapid establishment of open-shelf conditions. The shelf was then blanketed by shales.

The reduced character of black shale at the base of the shale section implies conditions at first were quiet and euxinic. This suggests the shelf deepened or circulation on the shelf was restricted in some way by a barrier on the outer shelf. Consequently, the shelf waters may have became stratified, facilitating oxygen-poor bottom conditions. Influx onto the shelf of cooler, oceanic water low in $O_2$ due to high organic productivity (Demaison and Moores, 1980) may have contributed to this effect. This seems possible since the Early Cambrian shelf was probably open to Iapetus Ocean, which at that time was fairly narrow and did not have good oceanic circulation.

Olenellid trilobites, which are scattered as complete bodies in the shales or concentrated as disarticulated parts in layers, aid somewhat in the interpretation of the shale environment. The mode of life of olenellid trilobites was essentially vagile benthonic. It is likely they lived on or close to the sea floor and were bottom sediment feeders. If this is correct, then clearly the truly anaerobic conditions must have prevailed below the sediment-water interface, rather-than above. This is supported by the abundance of *Planolites* burrows in the basal 7 m of the shale section and by several horizons of shallow bioturbation, penetrating only the top few centimetres of sea-floor mud. Fossil-rich packstone layers, which are intensely bioturbated, may be storm layers that by their organic-rich, porous nature were more favourable to host a burrowing infauna. Trilobite-rich layers may have been produced by the winnowing action of bottom currents or were introduced by storms. Equally possible however, these skeletal layers may represent episodes of mass mortality caused by an abrupt change in the physico-chemical environment. Gall (1983) suggests such events include turbid water conditions, as when major storms stir up fetid bottom muds, the release of $H_2S$ gas and the upwelling or mixing of poisoned bottom waters into an organism's habitat, each likely to cause asphyxiation. To date, no equivocal evidence for major storms reworking bottom muds has been seen, so it is possible the mass mortality mechanisms may be the cause. This is supported by the frequent articulation of body parts in the trilobite remains.

In Labrador, laterally equivalent strata reveal numerous archaeocyathid patch reefs. These are interpreted as stratigraphic reefs that thrived on the inner part of the shelf associated with an 'open shelf' facies of intercalated limestones, siltstones and shales (James and Kobluk, 1978).

Open-shelf conditions gradually became more important above the shale basin. The shelf aggraded, by the regular deposition of sheeted, highly bioturbated sublittoral sands (cf. Golding and Bridges, 1973), upon a muddy shelf. The sands were perhaps deposited by periodic discharge from a major river system. On the other hand, they may represent storm deposits laid down when sand was eroded from near shore and transported out onto the shelf. The small-scale sedimentary structures in the sands suggest they were deposited by weak currents. Small wave-generated, symmetrical ripple marks on the top of beds support this conclusion. However, some wavy lamination may indicate storm-generated hummocky cross-stratification. The favourable environment hosted an abundant soft-bodied infauna characteristic of shallow subtidal shelf settings (cf. Chamberlain, 1978).

Upward, the 'open shelf' facies passed rapidly into grainy and sandy carbonates that dominate the remaining part of the Forteau Formation. They are deposits of high-energy, nearshore to shoreline tidal sand bodies and shoals. The well-sorted oolitic and skeletal lime grainstones that dominate this

succession are typified by herringbone crossbedding, and crosslamination, planar to wavy thin bedding and minor bioturbation. These characteristics attest to deposition in a high- to moderate-energy tidal environment such as subtidal to intertidal sand flats and tidal deltas. Dolomite mudstone drapes and layers of intraclastic rudite, composed exclusively of dolostone clasts in some of the oolitic grainstones, suggest locally, these shoals were emergent as more sheltered intertidal areas. There, carbonate muds were deposited, perhaps desiccated, and then reworked during storms. Rudites, composed of lithified oolitic grainstone lithoclasts, show early cementation of the shoal sands occurred perhaps subtidally when the oolite shoal became locally inactive (Halley *et al.*, 1983). Oolite sands in modern environments commonly contain hard grounds that develop on the flanks of sand bars and on beaches (Halley *et al.*, 1983).

Prospering in the early stages of this high-energy, shallow-shelf were robust archaeocyathid build-ups. These correlate with the uppermost archaeocyathids of southern Labrador, which James and Kobluk (1978) and Hughes (1979) interpret as biostromes. The build-ups are associated with fringes of rubbly and well-sorted skeletal lime sands. The build-ups appear to thin southward toward Hawkes Bay. There, they are overlain by calcareous sandstone and sandy, oolitic grainstone, which blanket an area at least 13 km wide across the regional northeast strike of the rocks in the Hawkes Bay–Western Brook Pond area. These prominently crossbedded sands are apparently restricted in their distribution because they do not occur in the north of the area at Mount St. Margaret. The deposit, although possessing polymodal current directions, is dominated by southwestward directed crossbeds. The trough crossbeds, which are of equal size, are separated by erosion surfaces and characteristically lens out down direction and climb gently over the back of earlier sets. They probably formed as a series of dunes that migrated across a shoal sand and accreted by repeated episodes of storm- and fairweather-generated deposition.

Fossiliferous, glauconitic, bioturbated, sheet sandstones and shales rich in *Salterella* complete the Forteau Formation. They suggest the high-energy carbonate shoals gave way rapidly to less-agitated, deeper water, 'open shelf' sedimentation prior to the deposition of quartzose sandstones of the Hawke Bay Formation.

### *Hawke Bay Formation*

#### *Definition and Distribution*

The Hawke Bay Formation is the name given to a late Early Cambrian sequence of dominantly white quartz arenites, which are interbedded with some white, red and grey argillaceous sandstones and grey, green-grey and red shales and siltstones. The name is that originally used by Schuchert and Dunbar (1934) and by many subsequent workers (Johnson, 1949; Nelson, 1955; Woodard, 1957; Whittington and Kindle, 1969; Smit, 1971; Swett and Smit, 1972) for the upper formation of the Labrador Group. The formation, as they each defined it however, included carbonate rocks of Middle and Late Cambrian age overlying white quartzites of Early Cambrian age.

The present definition of the formation is that used by Knight (1977) although he first informally referred to it as the Hawkes Bay quartzite formation. Also, the definition is clearly that proposed long before by Richardson for his division C of the Potsdam Group (Logan, 1863). In this revised definition, the formation begins at the first white quartz arenite unit overlying the grey shales and sandstones of the top of the Forteau Formation. It continues to the top of the last quartz arenite bed below a black shale unit, which marks the base of the overlying Middle Cambrian March Point Formation. The lower and upper contacts are exposed and partly exposed on the south shore of Hawkes Bay, 0.6 and 4.5 km respectively, west of the town of Hawkes Bay. The upper contact is exposed on the north shore of Hawkes Bay, 1.6 km west of the mouth of Big East River. It is also poorly exposed at a number of localities on Western Brook Pond and on Indian Steady (Port Saunders map sheet). Both contacts are conformable. The type section for the formation occurs on the southern shore of Hawkes Bay, and although gently folded, it has been compiled by tracing beds around folds (see Figure 3, and Appendix 1, Section 1).

The formation is not only distributed on the southern shore and northeast corner of Hawkes Bay and along the outer course of Big East River but also caps the North and South summits of the Highlands of St. John. Furthermore, it underlies a heathland west of Lady Worcester Brook, outcrops along the shore and islands of Western Brook Pond, and forms a number of northeast-trending ridges east of the middle course of Big East River.

#### *Thickness*

The formation is approximately 150 m thick. It consists of gently folded and fairly well-exposed strata along the southern shore of Hawkes Bay (Knight, 1977). Schuchert and Dunbar (1934) measured only about 47 m of quartzite and the interbedded rock types (Schuchert and Dunbar, 1934, Units 2 to 9, page 24) that would be contained in the presently defined formation. Nelson (1955, Units 1 to 4, page 21) gave 130 m as the approximate thickness of the formation on the south shore of Hawkes Bay.

#### *Lithology*

The Hawke Bay Formation consists mostly of yellowish resistant weathering, white, pink and infrequently green, purple and red quartz arenites. These are interbedded with more easily weathered, red sandstones and shales, rusty-weathering, off-white and grey sandstones, and green-grey to grey shales interbedded with thin grey sandstones and phosphatic sandstones.

*a) Quartz-Arenite Lithofacies.* Quartz arenite is the main facies in the formation. It is thick bedded, massive, hard and well cemented. It is generally well sorted, clean, very fine to medium grained, although some coarser grained

sandstones, granular and pebbly sandstones also occur; pebble layers are rare. The granules and pebbles, which rarely exceed 1 cm to 2 cm diameter, are rounded to subrounded. They consist of white, pink and opalescent blue quartz and rare red granite; red sandstone and shale intraclasts occur in some quartz arenites where they overlie nearby red and white sandstones and shales. The quartz arenites are made up mostly of 'common' quartz with rare equant, granoblastic and schistose metamorphic quartz. Microcline and dusty orthoclase grains are infrequent; in thin section, they visually form less than 5 percent of the rock. Zircon, magnetite and sphene are scattered in the arenites and also concentrated in heavy mineral-rich laminae. The sandstones are cemented into a hard, flinty rock by grain overgrowths of quartz.

The quartz arenites display abundant trough crossbedding, planar crossbedding and some units of planar stratification. The trough crossbeds, which may reach 35 cm in thickness, are mostly 5 to 20 cm thick. They include long cylindrical troughs several metres in length and 50 to 100 cm wide, as well as short scoop-shaped troughs 50 cm wide and long. Planar cross-stratification is not as common but includes 5- to 30-cm-thick sets composed of straight, tabular foresets overlying planar basal scours. Smaller sets in some instances are accompanied by straight ripple marks on upper bedding surfaces. However, some large cosets (Plate 9) of planar tabular cross-stratification, 40 to 80 cm thick, composed of 6- to 15-cm-thick foresets, occur on the south shore of Hawkes Bay. They have dominantly northeast-directed avalanche faces. The strike length of the avalanche face of some sets is several metres and the sets are traceable for more than 4 m downcurrent. Pebbly and granular coarse sandstone and granule conglomerate that grade up into medium-grained sandstone compose the sets. Straight ripple marks are superimposed on the foreset face of one set of southeastward-directed planar cross-stratification; the ripple marks show that a northeast current flowed across the avalanche face of the set.

Wave- and current-ripple marks common on many bedding planes include straight, sinuous, bifurcating and linguoid forms. (Rib-and-furrow structures and ripple crosslamination may also be associated.) Green-grey mudstone drapes occur rarely on rippled bedding planes and in shallow depressions. Some mudcracks (possibly syneresis cracks) were noted on a few of the mud-draped surfaces. Planar thin stratification is not common but appears to occur in fine-grained sandstones, many of which are reddish; heavy-mineral laminations and parting lineations are commonly associated. Other structures in the quartz arenites include convolute deformation of crossbeds, which may involve up to 2 m of strata and water-escape structures. The water-escape structure (synonymous with the sand volcano of Knight, 1977) occurs in a small cove a few hundred metres west of the mouth of Otter Brook. It is a 30-cm-diameter circular depression (Plate 10) interrupting a ripple-marked bedding plane. Within and to one side of the depression, there is a circular, 13-cm-wide inner pit. This is partly surrounded on one side by a semicircular raised lip of sandstone on the open side of the main depression; the pit is partly filled by siltstone.

**Plate 9.** *Large-scale, planar cross-stratification in white quartz arenite of the Hawke Bay Formation, south shore of Hawkes Bay. The avalanche face is gently curved and faces the northeast.*

**Plate 10.** *Circular mud-filled depression interpreted to have formed when a spring welled up through ripple-marked beach sands, Hawke Bay Formation, south shore of Hawkes Bay.*

In general, the crossbedded quartz arenites lack fossils and bioturbation. However, where the arenites underlie grey or red argillaceous sandstones, the upper surface, and in some instances the top 20 cm of a quartz-arenite unit, are strongly burrowed and pitted by resting traces and U-shaped burrows.

*b) Bioturbated, Argillaceous Sandstone Lithofacies.* Grey, red and white, argillaceous and in some instances rusty-weathering sandstones in units up to 4 m thick form a second

facies that composes only 9 percent of the formation. They are characteristically rusty or red spotted because of the presence of pyrite in the sandstones. Petrographically, the sandstones include both well-sorted, very fine-grained and poorly sorted, medium-grained and locally argillaceous, calcite-cemented sandstones. The sandstones are quartz dominated but contain marginally more microcline as well as sericite, muscovite and chlorite than the white quartz arenites. Rounded glauconite grains occur in sandstones toward the base of the type section. Grey sandstones are generally more argillaceous; red to pink sandstones have limonite and hematite coating sand grains.

These sandstones have been extensively bioturbated. However, two subfacies occur in these sandstones. The first is found intercalated abruptly within the quartz arenites and is best illustrated by a sequence, 5.8 m thick (Unit 2, Figure 3), on the north shore of Hawkes Bay. Similiar rocks are seen near the top of the formation on Indian Steady (Torrent River map sheet) and just downstream of the roadbridge over Big East River. It consists essentially of 1- to 15-cm-thick flaggy beds of very fine- to fine- and only rarely, medium-grained sandstones. The succession is composed of thicker units of bedded sandstone, up to 65 cm thick, alternating with beds, 10 to 35 cm thick, of 1- to 5-cm-thick flaggy sandstones having shale partings and thin beds (Plate 11). In some instances, the sandstones intercalated with the shales are nodular and lenticular. The dominant sedimentary structure in the sandstone is planar lamination that locally displays parting lineations. However, ripple crosslamination and small symmetrical and linguoid ripple marks are preserved. Triple-pointed, incomplete mudcracks occur in shale partings near the top of the section. Bioturbation is ubiquitious throughout the section although some thicker laminated sandstones may be free of burrows or only sparsely burrowed. The main trace fossils are simple and spreite-filled U-shaped burrows, *Arenicolites* and possibly *Corophioides*. Subhorizontal or wandering tubular burrows, *Planolites*, are less common.

The second subfacies is found in the lower 60 m of the formation, where it lies immediately beneath white pebbly quartz arenites and above a covered interval, which is believed to conceal a section of shale that is exposed at Otter Brook (see lithofacies D). White, grey and red, locally glauconitic sandstones occur in beds generally 5 to 20 cm thick, separated by thin shale beds or partings whose colours correspond to the colour of the accompanying sandstones. Internally, the sandstones display planar lamination and ripple crosslamination and possess planar to locally scoured bases. Straight and linguoid ripple marks occur on bedding surfaces. Trace fossils are common in the lithofacies and include crawling and resting traces, and burrows. *Cruziana* and *Rusophycus* occur on the bases of both red and white sandstones. Simple vertical burrows, probably *Skolithus* as well as U-shaped burrows, *Arenicolites* and *Diplocraterion* are present. Shrinkage cracks were noted on the base of a block of red sandstone.

*c) Interbedded Brown Siltstone and Sandstone Lithofacies.* Interbedded brown-weathering, grey shaly siltstone and very fine sandstone in a sequence (Unit 11, Figure 3) up to 1.96 m thick (Plate 12) constitutes a third facies, although a minor element of the type section. Beds are mostly less than 30 cm thick and composed of uneven to planar thin bedding and lamination. They also include flaser bedding and lenses of intraformational conglomerate. The intraformational conglomerates are composed of indeterminate organic remains and phosphatic intraclasts, which were derived from erosion of phosphate-cemented sandstone and siltstone. Simple tubular burrows and *Corophioides*, many blackened by a phosphatic(?) coating, are common.

*d) Shale Lithofacies.* The fourth facies that comprises 20 percent of the formation dominantly consists of green-grey shale with interbeds of green, well-sorted, slightly glauconitic, locally graded, very fine-grained sandstone. It is at least 20 to 30 m thick and is partly exposed at the mouth of Otter Brook. The shales are rich in hyolithids and contain the trilobite *Olenellus fremonti*. The interbedded sandstones are generally less than 10 cm thick and lens-out over a few metres. They are either massive with some phosphate and shale intraclasts or planar laminated. Plug-shaped burrows, brush marks similar to *Curvolithus* (Hantzschel, 1966) on bases, and parting lineations and some ripple marks on bedding tops occur on the sandstone beds. Sandstone dykes, 3.5 cm wide and folded by compaction transgress the shales for several metres.

### *Paleocurrents*

Paleocurrents were measured on crossbeds in the quartz arenite units of the Hawke Bay Formation and are shown in rose diagrams (Figure 4). Vector means for different stations vary from 163 to 330° but the greater number of the vectors lie within 20° north or south of due east, suggesting dominantly eastwardly directed paleoflow. Bimodal–bipolar and polymodal distributions do occur but one vector clearly dominates in most rose diagrams. Planar cross-stratification, plotted separately, shows the same eastward vector. However, a major proportion of the planar crossbeds face northeast, including all the very large sets described in detail above.

### *Age*

*Olenellus fremonti* Walcott found together with hyolithids only 30 m above the base of the formation suggests the lowest beds of the formation are of late Early Cambrian age and belong to the *Bonnia–Olenellus* Zone of Fritz (1972). So far, the formation has yielded no other fossils in the map area.

### *Depositional Environment*

General knowledge of the great areal extent of the sandstones of the Hawke Bay Formation in northwestern Newfoundland suggests that they are a blanket sandstone deposit underlying an area greater than 100 by 65 km in size. The formation is characterized by well-sorted, mature quartz arenite that displays some bipolar–bimodal and polymodal paleocurrent distributions, and is associated with beds containing marine fossils and shallow-marine trace fossils.

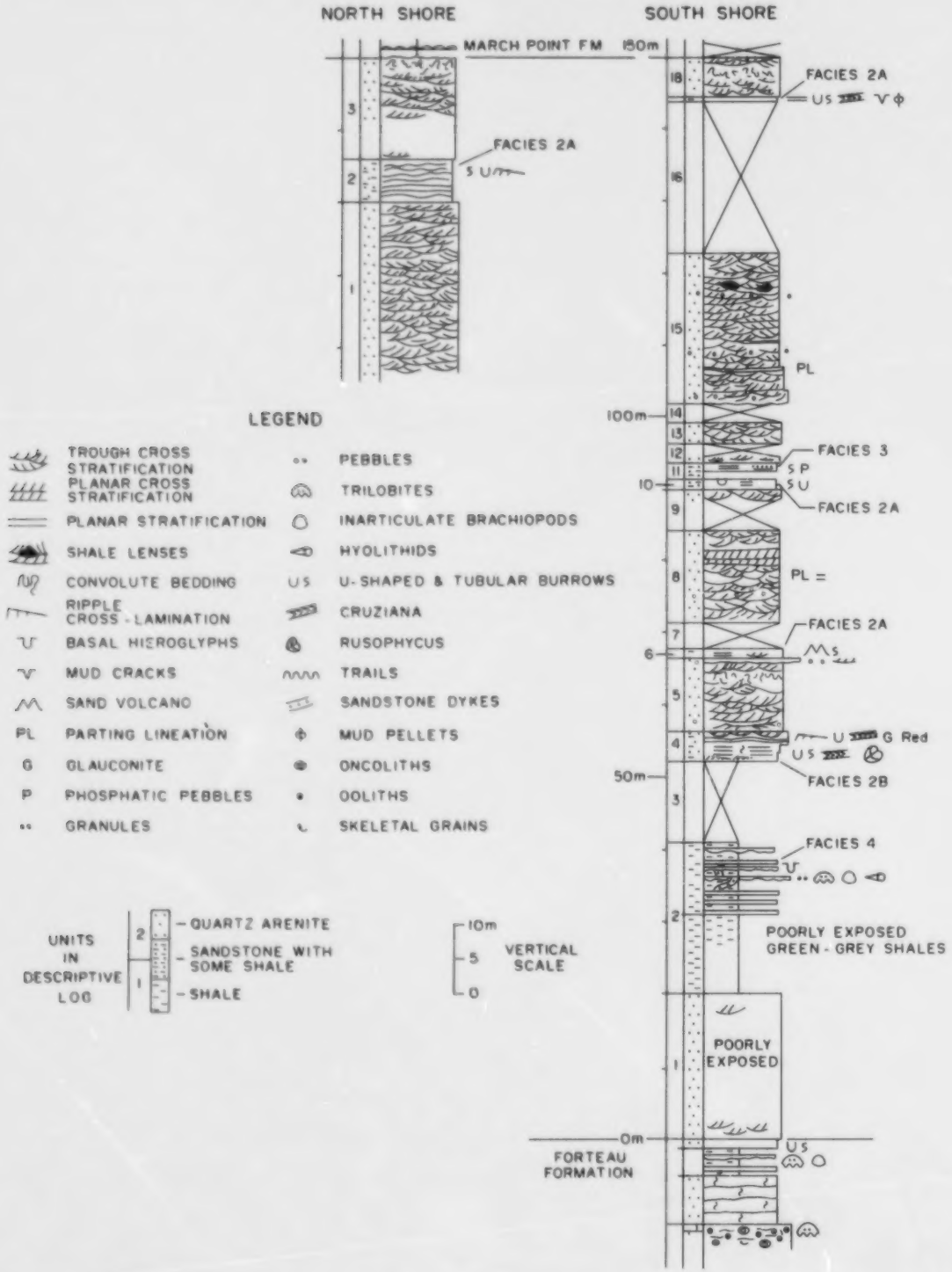



**Figure 3.** *Schematic section through the Hawke Bay Formation, along the shores of Hawkes Bay.*

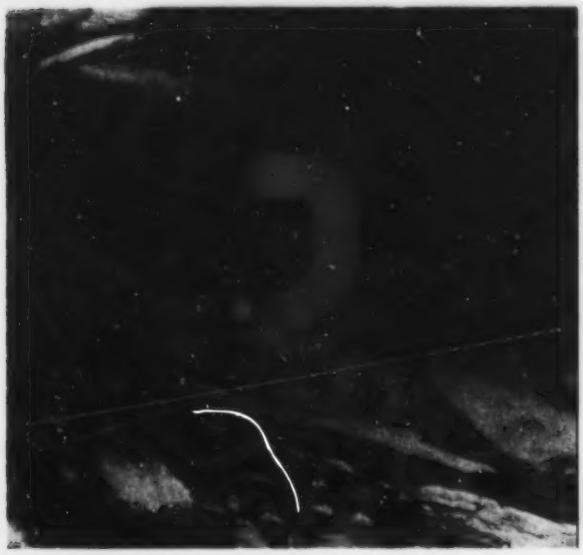


**Plate 11.** *Interbedded shale and white sandstone of lithofacies B, Hawke Bay Formation, north shore of Hawkes Bay. The sandstones are rich in U-shaped burrows.*

**Plate 12.** *Dark-grey, thinly bedded, silty mudstone (lithofacies C) of the Hawke Bay Formation, south shore of Hawkes Bay. The mudstones are bioturbated.*

These characteristics plainly point to a tidally dominated, shallow-marine depositional setting for the formation. A thick, areally extensive deposit of fairly uniform character favours special conditions of deposition (Klein and Ryer, 1978). These must have included an abundant supply of sandy detritus, and a wide shallow-shelf that allowed high-energy tidal currents not only to sort and mature the sand but also to produce the abundance of current stratification and ripple marks that attest to the tidal origin for the quartz arenites of the formation.

However, other facies in the formation indicate that shelf conditions were not always of the nature already described. In the lower 60 m of the formation, quartz arenites are the topmost part of coarsening- or maturing-upward sequences that consist of shale and thin sandstone, bioturbated sandstone and the quartz arenite. Two such sequences occur. The first includes the topmost interval of the Forteau Formation consisting of intercalated fossiliferous shale and bioturbated sandstone and the basal white quartz arenite unit of the Hawke Bay Formation.

A deeper water offshore setting is interpreted for the green-grey shale and thin sandstone facies that characterizes the base of the sequences. The thin, fine-grained and sometimes graded sandstones display structures including current markings and upper-flow-regime plane beds to lower-flow-regime current ripples on tops of some beds. This suggests they may have been deposited by decelerating low-density turbidity currents that were perhaps generated when storms remobilized sediment on shallower areas of the shelf. Olenellid trilobites and hyolithids flourished in this deeper, generally quiet environment that lay below wave base.

Although exposure is not good, the shale facies is probably directly overlain by a succession of bioturbated grey, white and red sandstones and some intercalated shales. Except for one bed carrying shrinkage cracks that may well be syneresis cracks, there is no evidence of subaerial exposure in these sandstones and shales. The sandstones are glauconitic and argillaceous, consist of small-scale sedimentary structures, and are rich in trace fossils, which are characteristic of shallow offshore sandy settings (Chamberlain, 1978; Seilacher, 1978; Crimes, 1970). These features suggest that they were laid down in generally low-energy, subtidal conditions, perhaps typical of the lower nearshore zone (Davis, 1978). Thicker sand beds composed of scoured bases and cross-stratification likely represent storm deposits swept into the quiet nearshore setting. The white quartz arenites abruptly rest upon the bioturbated sandstone facies. Such an upward maturing or coarsening sequence is generally believed to be characteristic of a prograding shoreline having offshore facies overlain by nearshore facies and then by nearshore and possibly intertidal facies.

Overlying this sequence, the succession appears to be dominated by the white quartz arenite facies. Their well-sorted mature nature, abundance of cross-stratification, paleocurrents and lack of trace fossils suggest they were deposited in a shifting, high-energy nearshore and/or intertidal setting. Possible settings might include beach and longshore bars, subtidal and intertidal-flats, tidal channels and deltas and tidal sand bodies associated with a meso- or macro-tidal shelf sea (Davis, 1978; Boothroyd, 1978; Klein, 1977).

The scale and form of cross-stratification appears to rule out deeper water sand bodies such as described for open shelves by Swie-Dyin (1976). Rather, the stratification suggests cross-strata associated with trains of cuspate megaripple, linear sand waves and larger transverse bars deposited in shallow water. Units of upper-flow planar lamination along

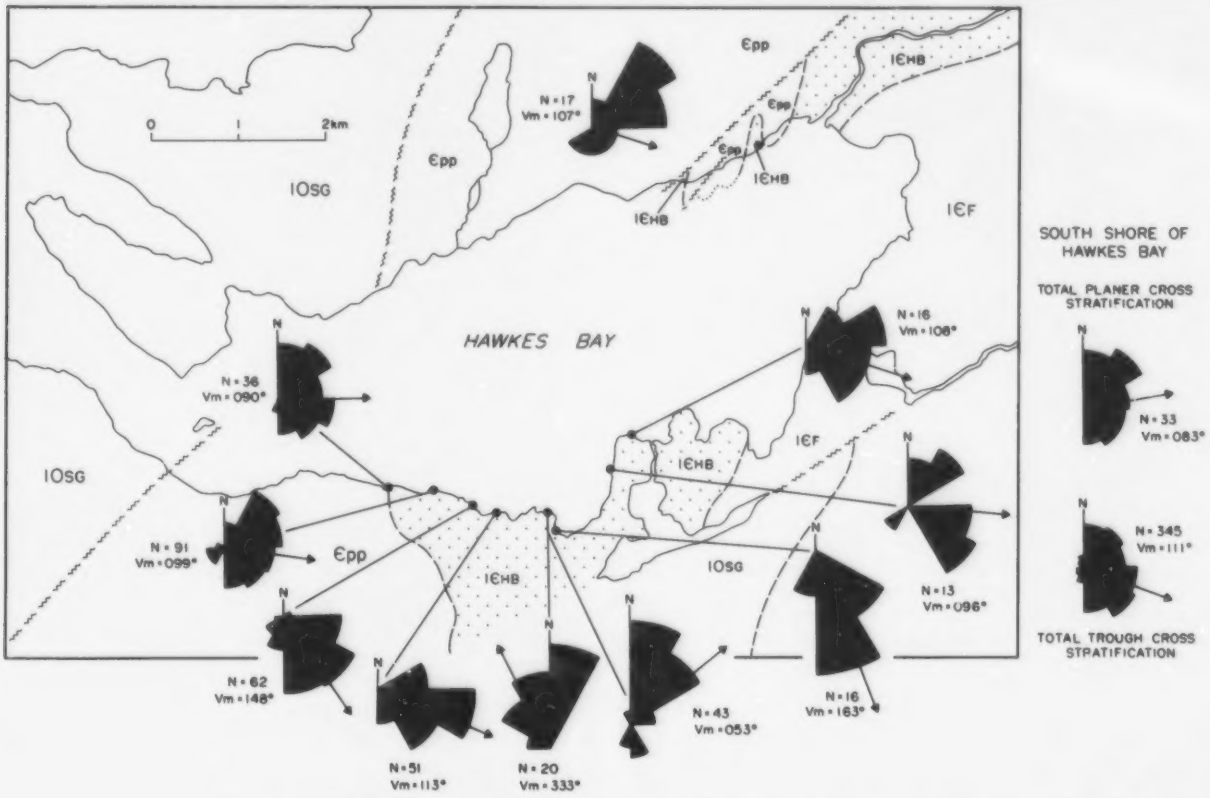



**Figure 4.** *Rose diagrams of crossbeds, Hawke Bay Formation, Hawkes Bay.*

with cross-stratified sands imply that locally, high-flow strength typical of the swash zone (Boothroyd, 1978) occurred. The shifting bipolar and polymodal paleocurrent distributions, the preservation of water-escape structures together with wave- and current-generated ripple marks, including ladder ripples, and the preservation of ripple marks that migrated laterally along the face of tabular foresets, strongly suggest that the environment was shallow subtidal to intertidal and hence nearshore or shoreline.

The paleocurrents show that sand was dominantly moved eastward and this sense of movement is consistent in both planar and trough crossbeds. The largest planar crossbeds, probably constructed in transverse bars, give a consistent northeastward vector. This evidence may help to better define the actual depositional environment. Study of many Holocene shoreline settings dominated by tidal currents show that the dominant current vector is shoreward in both cuspate megaripples and large-scale sand waves or bars. This dominant direction of structures is maintained even when a major sand body is constructed under dominantly ebb conditions, e.g., on an ebb tidal delta (Boothroyd, 1978). If this is applied to the Hawke Bay sandstones, it would suggest a shoreline lay to the east.

However, in reconstructions of the Cambrian shelf of western Newfoundland, it is generally assumed that the shoreline lay to the northwest and trended northeast to east. Paleocurrents in fluvial beds of the Bradore Formation generally provide the best evidence of this conclusion (see above and James and Hiscott, 1982; Hiscott *et al.*, 1984). If this reconstruction is correct, then most of the sand in the Hawke Bay Formation was being moved away from (i.e., southeastward) and parallel to (i.e., northeastward) the shore. The model thus promoted here and also suggested by Klein (1977) and other workers (e.g., Swett and Smit, 1972b) for similar quartz arenites favours an open, shallow, tidally dominated shelf with a complex of shifting sand bodies of subtidal and intertidal origin. Stratification and bedforms of similar scale to those noted in the formation are described in intertidal sand bodies of the Bay of Fundy (Klein, 1970; Dalrymple *et al.*, 1978), an area influenced by very large tides. An alternate and somewhat controversial origin for the bulk of these sands is that they are dominantly fluvial with lesser amounts of marine shoreline deposits. The predominance of eastward-directed trough and planar crossbeds throughout the facies hints that this idea may be valid. The absence of sequences in the sands would suggest the fluvial regime was dominated by shifting channel systems adjacent to the shoreline.

Two other facies also occur in the succession. The first of thinly bedded, sparsely bioturbated, argillaceous grey sandstones and siltstone (lithofacies C) contains phosphate-cemented sand beds and phosphatic-intraformational conglomerates. The second consists of thinly bedded, bioturbated, very fine-grained quartzose sandstones having

minor shales. Both were deposited intertidally, the first possibly on a sheltered muddy sand flat, in which early phosphatic cementation occurred. The second facies, which is rich in U-shaped burrows, may compare to the inner *Arenicola* sand flats of some modern intertidal-flats. Ripple marks and ripple crosslamination suggest currents with low-flow strengths were common on the intertidal flats. Nonetheless, the importance of flaggy beds of upper-flow planar lamination suggest storm conditions produced plane beds probably in the swash zone. Clearly, abundance of burrows and the deposition of partings and thin beds of shale implies that sand deposition was intermittent, the burrowing infauna proliferating during fair weather conditions.

# CAMBRIAN CARBONATES

## Port au Port Group

Strata of Middle and Late Cambrian age including limestones, dolostones and shales conformably overlie the Labrador Group. The succession comprises the March Point Formation and Petit Jardin Formation. These formations are better exposed and understood farther north on the Great Northern Peninsula (Knight, 1977, 1980) and to the south on the Port au Port Peninsula (Levesque, 1977; James *et al.*, 1983). In earlier reports by Knight (1977, 1978), these two respective rock units were named informally the 'Micrite formation' and 'Dolomite formation'.

### *March Point Formation*

*Definition and Distribution*

The March Point Formation consists of dolostones and dark grey shales of Middle Cambrian age; some thin sandstones interbedded with shales occur at the base of the formation. In the map area, the formation is generally poorly exposed. It outcrops in fault-bound, folded outcrops on the north and south shores of Hawkes Bay. It is also exposed along a woods road in the southeast corner of the Port Saunders map sheet and in the vicinity of Pikes Feeder Pond and north of Indian Steady on the Torrent River map sheet. It also outcrops in shoreline exposures on Western Brook Pond.

The lower contact of the formation is placed at the base of a 1.6- to 2.5-m shale and sandstone unit that lies conformably upon the last white quartz arenite bed of the Hawke Bay Formation (Figure 5). It is exposed on the north shore of Hawkes Bay 1.6 km west of the mouth of Big East River and at two localities on the northwest shore of Western Brook Pond. The same boundary on the south shore of Hawkes Bay occurs in a mud- and gravel-covered interval 4.5 km west of the town of Hawkes Bay. The upper contact is faulted out on the north shore of Hawkes Bay but is exposed on the south shore of the bay, 0.5 km east of Ourson Point. It is placed between cryptalgal dolostone beds and overlying interbedded red and green-grey shales and dolostones. It also outcrops on the north-trending woods road that branches off the main Mooney Block forest access road in the southeast corner of the Port Saunders map area.

*Thickness*

The formation is approximately 29 m thick on the south shore of Hawkes Bay. It is 70 m thick in the St. Barbe area, to the north, and 61 m thick on the Port au Port Peninsula (Levesque, 1977). It is calculated, structurally, to be approximately 50 m thick in the area southeast of Western Brook Pond.

*Lithology*

Dark-grey shale interbedded with thin sandstone in a basal unit is overlain by a middle unit of rusty-weathering, dark-grey dolostone and an upper unit of interbedded dolostone and thin shale and mudstone in the map area.

*a) Lower Shale–Sandstone.* At Hawkes Bay, the basal shale and sandstone unit (Plate 13) is 2.1 m thick. This unit begins with shale interbedded with 1- to 2-cm-thick calcareous siltstones, which are ripple-marked and slightly bioturbated. The middle of the unit is completely shale, which thins to partings between thin-bedded, very fine sandstones in the upper 90 cm of the unit. Inarticulate brachiopods occur in the shales that are mudcracked; bedding planes are ornamented by fine striae and trails. The sandstones at the top are platy, thin bedded, internally laminated and contain some shale flaser. *Arenicolites* and *Skolithus* were noted near the top of the sandstones. The topmost bed is a coarse-grained, glauconitic sandstone.

On Western Brook Pond, the shales are covered and only several beds, 5 to 15 cm thick, of black and white, coarse-grained siltstone to medium-grained sandstone are exposed. Most of these beds consist of black, laminated coarse siltstone–very fine sandstone interlaminated with black shale. Other beds consist of laminated, black, very fine sandstone and laminated, white, fine- to medium-grained sandstone. Small-scale scours are common in the shale–sandstone beds and a variety of small (1 mm) to large-diameter (1 cm) burrows, including *Skolithus*, and possibly *Teichichnus*, occur in the dark-coloured siliciclastics. Some of the larger burrows contain 1 mm phosphate grains. Trace fossils are rare in the white sandstones, which contain sand- and pebble-sized quartz grains and black phosphate intraclasts. Layers of phosphatic intraclasts, 1 to 3 cm thick, occur at the top of beds in the succession. One, massive phosphatic layer cements the top of a burrowed, interlaminated sandstone–shale bed.

*b) Middle Dolostone.* Throughout the area, the basal shale–sandstone is abruptly overlain by well-bedded, rusty-weathering, pyritic, shaly dolostone, which is approximately 14 m thick on the north shore of Hawkes Bay. It consists mostly of dolomite mudstones having interlayered grainstones and rudstones. Wavy to nodular thin bedding, flaser bedding, scour-and-fill structure, and some crosslamination characterize the mudstones (Plate 14). Thin structureless or planar-laminated beds also occur. Inarticulate brachiopods and sparse to abundant simple burrows occur in the mudstones. Small-scale, straight ripple marks, gutter casts

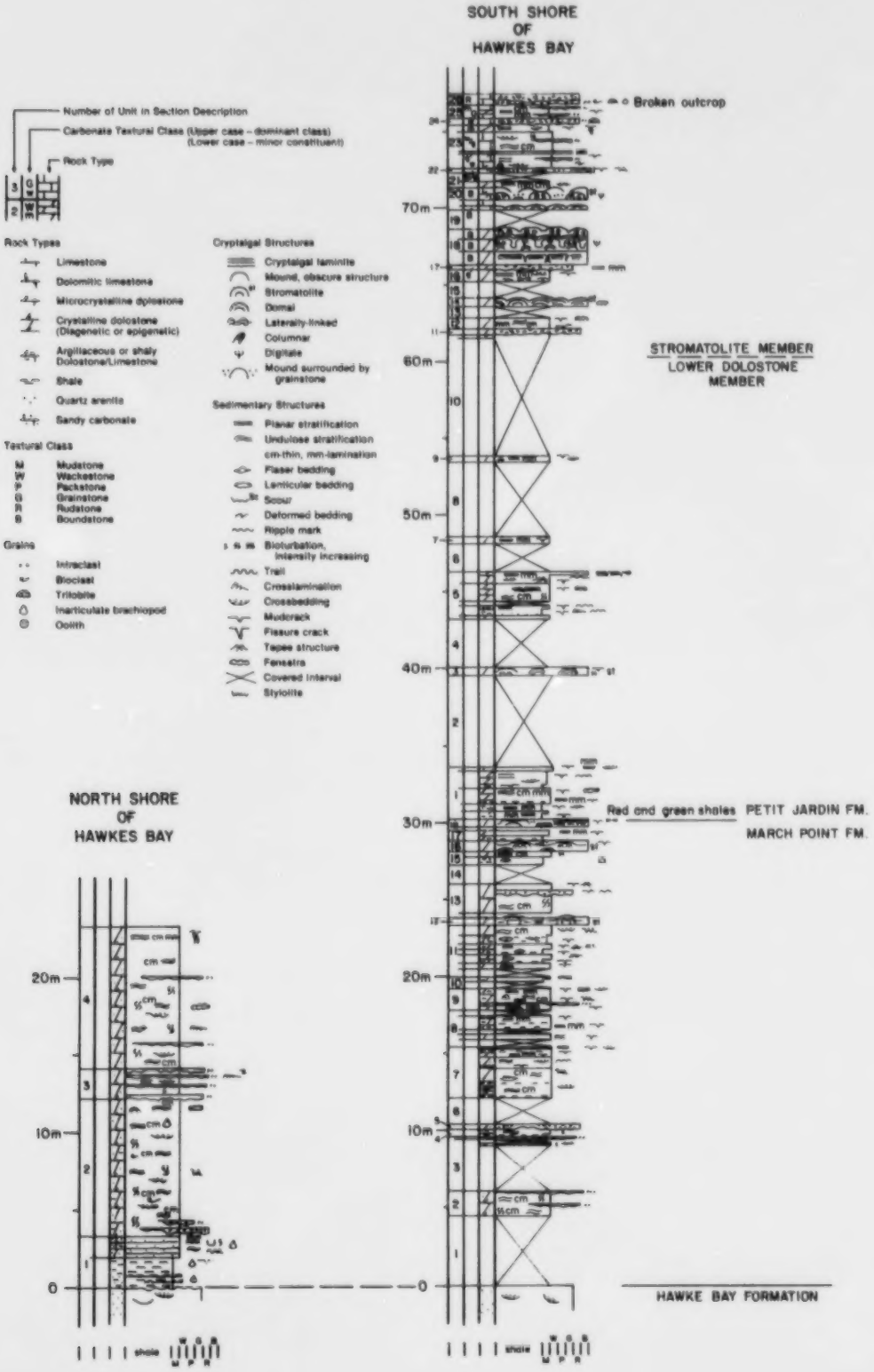

SOUTH SHORE OF HAWKES BAY
NORTH SHORE OF HAWKES BAY
Number of Unit in Section Description
Carbonate Textural Class (Upper case – dominant class) (Lower case – minor constituent)
Rock Type
Rock Types
Limestone
Dolomitic limestone
Microcrystalline dolostone
Crystalline dolostone (Diagenetic or epigenetic)
Argillaceous or shaly Dolostone/Limestone
Shale
Quartz arenite
Sandy carbonate
Textural Class
M Mudstone
W Wackestone
P Packstone
G Grainstone
R Rudstone
B Boundstone
Grains
Intraclast
Bioclast
Trilobite
Inarticulate brachiopod
Oolith
Cryptalgal Structures
Cryptalgal laminite
Mound, obscure structure
Stromatolite
Domal
Laterally-linked
Columnar
Digitate
Mound surrounded by grainstone
Sedimentary Structures
Planar stratification
Undulose stratification
cm-thin, mm-lamination
Flaser bedding
Lenticular bedding
Scour
Deformed bedding
Ripple mark
Bioturbation, intensity increasing
Trail
Crosslamination
Crossbedding
Mudcrack
Fissure crack
Tepee structure
Fenestra
Covered interval
Stylolite
Broken outcrop
70m
60m
50m
40m
30m
20m
10m
0
STROMATOLITE MEMBER
LOWER DOLOSTONE MEMBER
Red and green shales
PETIT JARDIN FM.
MARCH POINT FM.
HAWKE BAY FORMATION
shale

**Plate 13.** *Interbedded shale and sandstone overlain by bioturbated thinly bedded dolostone, base of the March Point Formation, north shore of Hawkes Bay.*

**Plate 14.** *A scour-based lens of edgewise intraformational breccia. The breccia lies within shaly, wavy thin-bedded, nodular and slightly bioturbated dolostone of the lower half of the March Point Formation, north shore of Hawkes Bay.*

and abundant spherical or rhomboid vugs, open or lined by quartz and dolomite spar, also occur.

Scour-based and gradational-based beds and lenses of intraformational dolomite rudstones, 1 to 6 cm thick, are interspersed in the dolomite mudstones. The lenses can be as small as 10 cm wide and 6 cm deep (see Plate 18b), suggesting some may be gutter casts. Rounded to platy intraclasts derived from the mudstones are internally structureless to laminated. Edgewise orientation and imbrication of clasts are common. The rudstones locally vanish laterally into the thinly bedded dolostones.

*c) Upper Dolostone–Shale.* Toward the top of this section, some beds, 30 to 50 cm thick, consist of a basal shale or planar-laminated shaly dolostone capped by wavy thin-bedded dolostone having lenses of intraformational rudstone. Mudcracks occur in the last meter of the 14 m interval.

The rock types described above appear to dominate the rest of the formation in the southeast of the map area as seen along the Mooney Block access roads. Along the south shore of Hawkes Bay, however, a succession of shales, shaly dolostones intercalated with dolostones, complete the remaining 15 m of the formation. The shales and dolostones are arranged in beds, 25 to 80 cm thick, consisting of a basal shale or shaly dolostone, 10 to 35 cm thick, resting sharply upon the underlying dolostone and passing upward gradationally into an upper dolostone (Plate 15). The shales are mostly grey to dark grey, dolomitic and laminated, with dolostone laminae and lenticular thin beds. Mudcracks

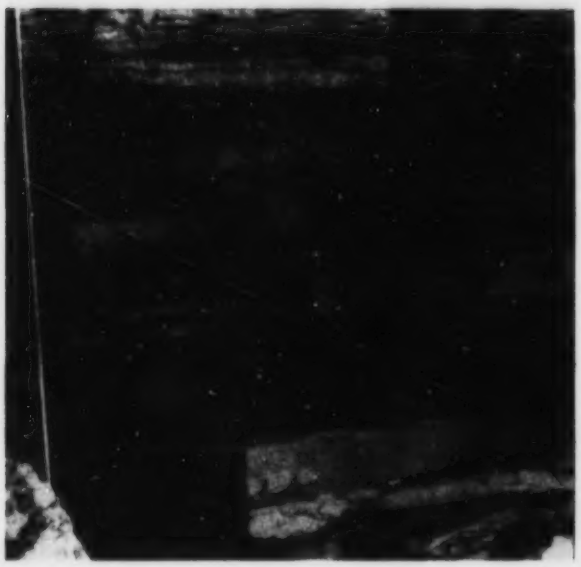


**Plate 15.** *Interbedded dolomitic shale and parallel-laminated and crosslaminated dolostone at the top of the March Point Formation, south shore of Hawkes Bay.*

**Figure 5.** *Schematic sections through the March Point Formation and the lower members of the Petit Jardin Formation, along the shores of Hawkes Bay.*

abound in most of the shales and shaly dolostone half-beds; wrinkle marks, linear shrinkage cracks, fissure cracks and adhesion ripples were noted in some of the shale half-beds.

The dolostone half-beds are also rich in desiccation cracks, which disrupt the smooth to wavy thin bedding and lamination (Plate 16); tepée structures occur in one bed. Pockets, thin beds and capping layers of intraformational dolomite grainstone, or rudstone, are common in the dolostones. Small, straight, symmetrical ripple marks and fenestra also occur.

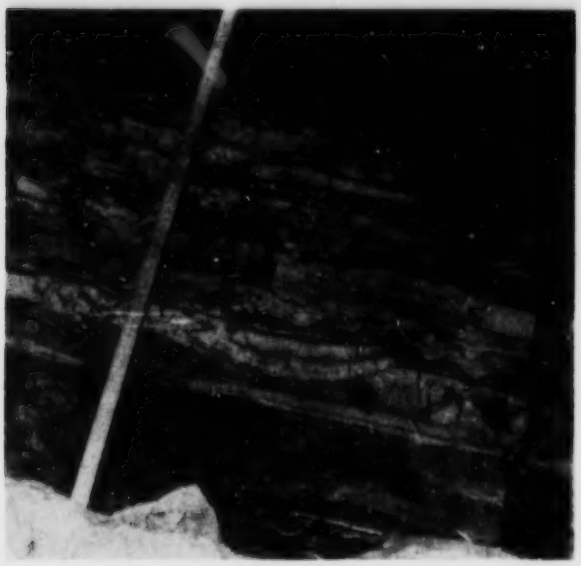


**Plate 16.** *Thinly bedded dolostone displaying parallel-lamination, scour-and-fill structures (lower arrow), desiccation cracks (upper arrows), possible tepée structures (middle arrow) and local pockets of* in situ *brecciation. Top of the March Point Formation, north shore of Hawkes Bay.*

In the last 7 m of the formation on the south shore of Hawkes Bay, the intercalated shales and dolostones give way to dolostones with some interbeds of hackly weathering, structureless, blue-grey mudstone; the latter contains inarticulate brachiopods. The dolostones include beds of uneven, thin-bedded, dolomite mudstone containing scour-based lenses and beds of intraformational rudstone. Mudcracked tops to beds are common.

However, also present are several beds of light-grey dolostone composed of cryptalgal boundstone mounds and laminites. The boundstones rest upon thinly bedded dolostones that may be bioturbated but lack mudcracks. The dolostones overlie dolomitic shale or blue-grey hackly weathering, fossiliferous mudstone. The cryptalgal mounds are constructed of smooth to crinkly, fine lamination and/or widely spaced,laterally linked hemispheroids, which radiate like a fan across the mounds. Smooth lamination composes the outermost zone of some mounds. The mounds can be spherical to irregular in shape. They attain 60 cm in thickness composed of three superposed beds 20 cm thick. Argillaceous seams occur between and within the beds picking out the mound shape. Mounds, 5 m in length, occur but most are less than 1 m in diameter. The mounds are isolated and surrounded by thin-bedded or fenestral dolostone having abundant mudcracks and fissure-cracks that pick out the margin of the mounds and intraclastic dolomite grainstone patches. However, in one of the sequences, the position usually occupied by the boundstone mounds is occupied by a 25-cm-thick grainstone bed, which is composed of intraclasts and possibly ooids. Both rock types are overlain by mudcracked, thinly bedded dolostone.

*Age*

The age of the March Point Formation on the Great Northern Peninsula is known to be late Middle Cambrian (Knight, 1977; Boyce, 1979; Boyce *in* Stouge and Boyce, 1983). No definitive Middle Cambrian faunas have been discovered in the map area although the inarticulate brachiopod *Lingulella* is quite common.

*Depositional Environment*

The sedimentary features of the March Point Formation suggest the formation, in the map area, was mainly laid down in an intertidal to supratidal depositional environment. An abrupt but conformable change occurs at the basal contact from high-energy, nearshore siliciclastic deposits of the Hawke Bay Formation to the finer grained, calcareous, low-energy, intertidal deposits of the March Point Formation. The shales interbedded with thin siltstones and sandstones at the base of the formation may represent a transition from the Hawke Bay setting to that of the first deposits of the carbonate platform. They are characterized by wave-ripple marks, planar and flaser bedding and minor mudcracks, which support an intertidal-flat interpretation for the basal sediments. Trace fossils, such as *Skolithus*, *Arenicolites* and possibly *Teichichnus*, which occur in the thin-bedded sandstones at the top of the shale member, are commonly associated in the lower sand flats of the intertidal environment (Crimes, 1975; Chamberlain, 1978). Inarticulate brachiopods live in muddy sub-environments of intertidal-flats in the absence of other faunas (Williams *et al.*, 1965).

Flaser- and wavy-thin bedding, scour-and-fill structures and intraformational rudstones in thin-bedded dolomite mudstones suggest that intertidal conditions continued as the first carbonates were deposited. Scour-based, intraclastic lime rudstones are probably deposits generated by storms that at intervals inundated the tidal flats and ripped up the fine sediments.

The lack of mudcracks in all but the top metre of these carbonate muds suggests a lower intertidal and perhaps subtidal setting. This interpretation is supported by the presence of bioturbation and inarticulate brachiopods that occur in the dolomite mudstones. Mudcracks developed on some bedding planes toward the top of the basal carbonates, suggesting the tidal flats gradually became emergent.

This emergent trend is reflected in the sediments of the remaining 15 m of the formation. The facies, characterized by repetitive sequences of mudstone and shale and laminated and stromatolitic dolostone, were deposited in a wide, low-gradient tidal flat. Abundant desiccation structures, fenestra (Shinn, 1983), tepée structures typical of early vadose lithification and diagenesis (Asserretto and Kendall, 1977; Ferguson *et al.*, 1982) and other small-scale structures suggest that the rocks accumulated high in the intertidal zone and most probably the supratidal zone (Shinn, 1983). The lack of evaporitic minerals suggests that the tidal flats were not true sabkhas.

The paucity of organic remains in the sequences suggests that salinity was quite severe. However, this may also imply that the mudstone–shale–dolostone sequences accumulated in tidal or supratidal ponds and lagoons rather than in tidal flats facing an open-marine shelf. The accumulation of argillaceous muds, some extensively desiccated and others with a sparce inarticulate brachiopod fauna, suggests both ephemeral and perennial water bodies. The fine argillaceous detritus may have been transported to the ponds as windblown dust and may also have been trapped on the subaerial flats by damp mud and algal mat surfaces where the water table breached the surface of the tidal flat. Algal mats that were preserved as laminated dolostones proliferated around the margins of the shallow ponds and on the damp flats bordering the ponds. The mats were extensively desiccated and lithified as the ponds dried up or water levels fluctuated. The algal mats accreted over the basal pond muds as the ponds were filled in, or as they shifted position on the tidal flats. Stromatolite mounds and locally intraclastic and oolitic carbonate sands accumulated in more exposed agitated geographic locations. These rocks, which overlie the mudstones having inarticulate brachiopods and capped by desiccated dololaminites, may possibly have accumulated around the shorelines of larger tidal lagoons. The sequences are typical of emergent, prograding tidal-flat sequences.

The formation is thinly developed (30 m) compared to other areas of the Northern Peninsula (70 m at St. Barbe, Knight, 1977; 90+ m Canada Bay, Knight and Saltman, 1980). This suggests that the area may have been a structural high during the Middle Cambrian. Although finally flooded by shallow seas, the area failed to accumulate much Middle Cambrian sediment and soon became emergent.

## *Petit Jardin Formation*

### *Definition and Distribution*

Dolostones and minor limestones and shales representative of the Late Cambrian Petit Jardin Formation underlie the northern margin of the Castors River map sheet and are exposed beneath low-lying ground over large areas of the Port Saunders sheet. The formation is poorly exposed in the map area, so that no continuously exposed sections occur. To the north in the St. Barbe coast area, the formation originally called the 'Dolomite formation' by Knight (1977, 1978) is divisible into four members. Although elements of these members are present in the area, no division of the formation into members is attempted on the map.

The formation overlies the March Point Formation conformably. The basal contact is placed at the base of a succession of red, green and grey shales that rest upon a stromatolitic dolostone. The contact occurs on the south shore of Hawkes Bay 0.5 km east of Ourson Point and also 2 km north along a branch road off the Mooney Block forest access road. The formation is in fault contact with the March Point Formation on the north shore of Hawkes Bay. Lower Ordovician rocks are faulted against higher strata of the Petit Jardin Formation across the Whale Factory Pond fault on the western mouth of the bay. The upper contact of the formation is elsewhere conformable with the overlying Watts Bight Formation (Knight, 1977, 1978). It is exposed at South Cove and in a road quarry on Route 73 on the Castors River map sheet, where it is also mapped inland to Three Mile Pond. The upper contact is exposed in a quarry near an abandoned loop of Route 73, just southeast of Hawkes Bay on the Port Saunders map sheet.

### *Thickness*

The thickness of the formation in the area is not known. It is at least 400 m thick on the St. Barbe coast to the north. Approximately 500 m has been calculated using structural cross sections in two different areas of the map sheet. Forty-six metres of poorly exposed section (Figure 5) were measured on the south shore of Hawkes Bay. Approximately 28 m of this consist of rocks comparable to the lower dolostone member of Knight (1977, 1980).

### *Lithology*

The dolostones of the Petit Jardin Formation are dominantly yellow weathering, light grey, very finely crystalline rocks. Only in dolostones that lie within the upper part of the formation are the dolostones also blue-grey to dark grey and many of these are of fine to medium crystal size. The dolostones are associated with some limestones and also with green, red, grey and black dolomitic shales. Chert occurs in the highest beds of the formation. Four formational members (Knight, 1978, 1980) are present in the area; lower dolostone, middle stromatolite, upper dolostone and cherty dolostone members.

*a) Lower Dolostone Member.* The oldest beds in the formation are exposed midway along the south shore of Hawkes Bay. Here, a sequence, approximately 47 m thick, belonging to the lower dolostone member, consists mostly of thinly bedded dolostones that are interbedded with intraclastic dolomite rudstones and red, grey, black and green shales and hackly weathering red and green mudstones (Plate 17). The shale, which is extensively mudcracked, is well laminated with variable amounts of dolostone laminae. Excellent mudcrack polygons are common. Layers of small-shale intraclasts and straight, very low amplitude (2 to 5 mm) ripple marks and some crosslamination occur, locally. The mudstones compose 10- to 30-cm structureless beds at the

**Plate 17.** *A shale–dolostone sequence from the base of the Petit Jardin Formation, south shore of Hawkes Bay. The shale is dark green-grey having locally reddened layers and spots; mudcracks are common.*

base of the shale units. In the Hawkes Bay section, multicoloured mudrocks form three sequences 100 cm thick that are gradationally overlain by dolostones. Well-exposed multicoloured shales and dolostones are also exposed along a north-trending woods road branching from the Mooney Block forest access road in the southeast corner of the Port Saunders map sheet.

The thin-bedded dolostones are composed of smooth planar lamination, flaser bedding, and of scour-based lenses of dolomite grainstone and granular intraclastic dolomite rudstone. Mudcracks and fenestra are common in the dolostones especially where these are repeatedly intercalated with intraformational grainy beds. Stylolites, small stromatolites, small, low-amplitude, straight symmetrical ripple marks and rare bioturbation also occur in the dolostones. Platy, generally laminated intraclasts up to 7 by 2 cm in size form the dolomite rudstones, which include well-sorted, edgewise conglomerates. Cryptalgal dololaminite encrusts clasts in one rudite bed. Definitive algal boundstone beds within the lower dolostone member are generally composed of cryptalgal laminite that on some bedding planes forms broad, flat to centrally depressed, irregular- to oval-shaped structures termed here 'pans' (Plate 18). The pans, which reach several metres across, are outlined by a series of long to short, locally branching, fissure cracks, 1 to 6 cm wide, of variable depth, that parallel the outer edge of each pan. Cryptalgal lamination is well displayed at the pan's edge, which is generally elevated a few centimetres above its centre. Uneven, smooth to corrugate (Hofmann, 1969) continuous lamination to layers of small, closely spaced, laterally linked hemispheroids occur. The marginal mat is locally in poor repair due to sheet and fissure cracks that split apart and crosscut laminae. Cryptalgal intraclasts are locally bound in the stromatolite. Shale drapes fill the fissure-cracks and depressions within and marginal to the pans.

*b) Middle Stromatolite Member.* Above the lower sequence on the southern shore of Hawkes Bay are rocks of Knight's (1978, 1980) middle stromatolite member. This member is characterized by thick beds of large domal stromatolites, which are separated by thinly bedded dolostones interbedded with intraformational dolomite rudstones and mudcracked dolostones. Stratigraphically higher beds of this member outcrop just east of the Whale Factory Pond fault on the north and south shores of Hawkes Bay. They include stromatolitic limestones and dolostones, oolitic lime grainstones, lime mudstones as well as the other ubiquituous dolostones. Some shales also occur. Beds of this same section are believed to be exposed in a quarry at the intersection of the Port Saunders road and Route 73.

The stromatolites occur in beds 30 to 180 cm thick. The thickest beds are composed of two or more mounds, some up to 70 cm thick. The stromatolites are spherical or more or less circular domal mounds but some upward-expanding; flat-topped, club-shaped structures also occur. The largest domal mounds reach 5 by 1.6 m in size. Internally, the domal mounds are constructed of thin layers of structureless and intraclastic dolostone interlayered with layers of crinkly, continuous lamination or ferruginous stylolitic layers (Plate 19). Structure is obscure in many mounds. However, laterally linked hemispheroids, digitate, collenia- and cryptozoan-type structures were noted in both lime and dolomite boundstones. One prominent succession of dolomite boundstones on the south shore of Hawkes Bay commences with flat cryptalgal laminite resting upon 20 cm of scour-based, intraclastic, sandy, dolomite grainstone. Deep, 1- to 2-cm-wide, branching fissure-cracks dissect this 100 cm bed, which is overlain by 85-cm-wide, large domal heads composed of 5- to 8-cm-wide, closely spaced, laterally linked hemispheroids capped by wrinkly, continuous laminite. The laminite blankets and smooths out the mounds and forms the substrate for a second mound bed, composed of laminite that is capped by beautifully developed, geniculate, very closely spaced, laterally linked hemispheroids, 2 to 3 cm in size.

Mounds composed of limestone close to the top of the exposed section, on the south shore of Hawkes Bay, consist of wispy, discontinuous lamination and 0.5-cm-wide, very closely spaced LLH structures that are stacked vertically, like inverted egg cartons up through 30 to 45 cm beds. However, when traced laterally, this form passes into slender, discrete digitate stromatolites. The mounds are surrounded by intraclastic lime rudstone.

a

b

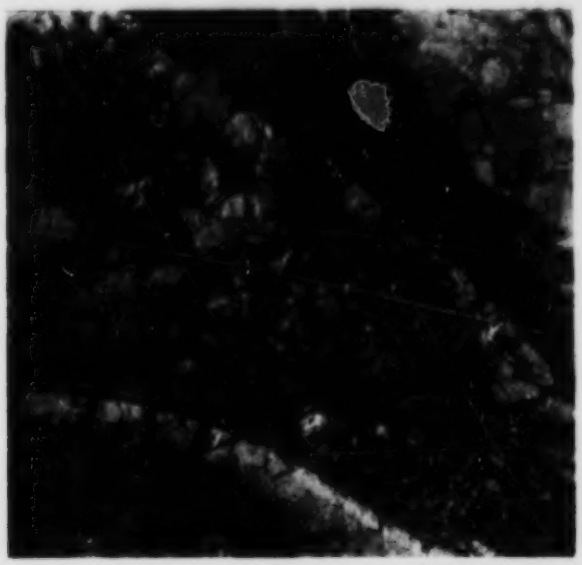


**Plate 18.** *(a) A circular pan of cryptalgal dolostone outlined by deep syndepositional shrinkage cracks (arrows). The pan is surrounded by thinly bedded dolostone, which is mudcracked and has intraclast-pavements (closeup Plate 18b). Basal member of the Petit Jardin Formation, south shore of Hawkes Bay.*

**Plate 19.** *Stromatolitic dolostone from the stromatolite member of the Petit Jardin Formation, south shore of Hawkes Bay. The large domal heads consist of closely spaced LLH and of crinkly, algal lamination.*

The stromatolites may rest upon intraclastic dolomite or lime rudstone, flaser- and lenticular-bedded dolostone or oolitic grainstone as seen on the north shore of Hawkes Bay (Figure 6). Here, oolitic grainstone also surrounds and onlaps the stromatolite build-up (Plate 20). The grainstones form beds 19 to 105 cm thick composed of trough and planar crossbedding and crosslamination; in some instances they show herringbone structure. Small scours and lenses and drapes of mudcracked dolostones, typify beds within the oolitic grainstone.

The centres of the ooids are typically composed of an inner zone of radial calcite surrounded by an outer zone of concentric lamination composed of micritic layers and dark cryptocrystalline laminae. Ghosts of concentric lamination can be distinguished in the outer part of the radial cortex. Some ooids have nuclei of very small ooids, which show concentric laminations. Intraclastic grains that occur in some grainstone beds include cemented oolite grains, mostly consisting of radial ooids, in some instances surrounded by a single sheath of tangential, very fine crystalline carbonate. Ooids within rare intraclasts preserve radial and concentric fabrics. Other intraclasts are composed of peloid-wackestone and packstone, and fine, equigranular, hypidiotopic dolomite. Radiaxial fibrous-bladed cements line open space between grains. This cement appears to postdate an earlier fibrous cement fringe to the allochems. Micrite-sized carbonate fills much of the space between grains in the intraclastic-oolitic grainstones. Rare skeletal fragments also occur.

The grainstones in this sequence are in turn overlain by mudcracked, flaser-bedded, crosslaminated and planar- to wavy-laminated dolostones (Plate 21). Small-scale scour-and-fill structures are common. In some instances, the dolostones are interlayered with thin, ripple-marked, oolitic grainstone beds. Bioturbation is present although rare in the dolostones. Inarticulate brachiopods were recovered from some of the thin-bedded shaly lime mudstone beds in the sequence.

Beds of oolitic grainstone are infrequent within the stromatolitic lime boundstones of the equivalent strata on the

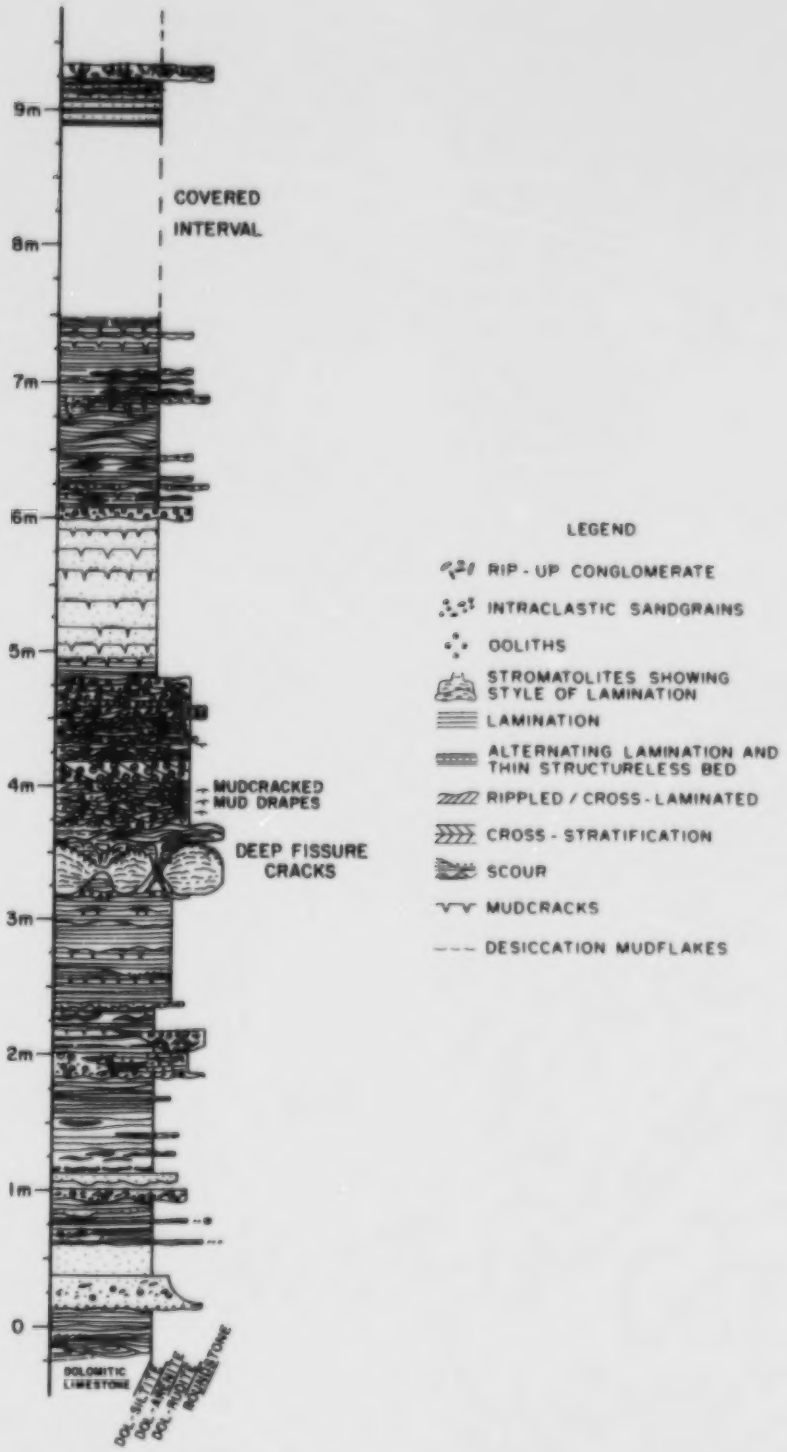



**Figure 6.** *Detailed graphic log of section (part of the Stromatolite member), Petit Jardin Formation, north shore of Hawkes Bay.*

**Plate 20.** *Thin-bedded, laminated dolostone overlain by a low bank of cryptalgal boundstone (lower arrow), which is capped by a bed of black, crosslaminated, oolitic grainstone (upper arrow). North shore of Hawkes Bay, Stromatolite member of the Petit Jardin Formation.*

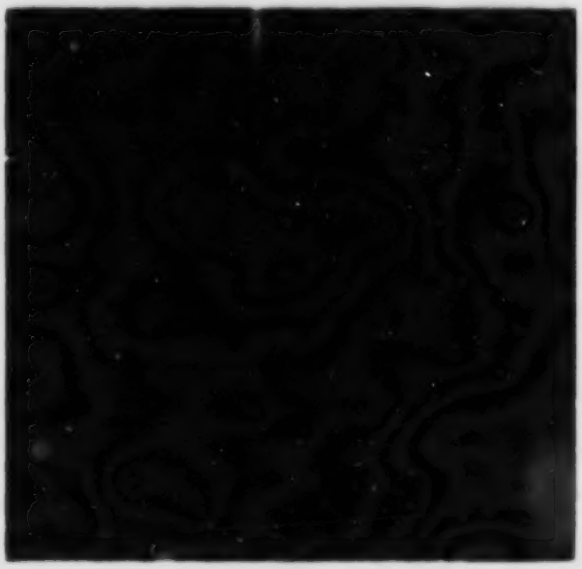


**Plate 21.** *Thin-bedded, laminated, crosslaminated and mudcracked dolostone having thin oolitic grainstone lenses (arrows). Mudcracks on overturned block (lower right). Stromatolite member, Petit Jardin Formation, north shore of Hawkes Bay.*

south shore of Hawkes Bay. Here, the stromatolites are overlain by thin-bedded, bioturbated and mudcracked lime wackestones and mudstones having some oolitic and skeletal grainstone beds or lenses. However, within these mudstones are initially lenses and then scour-based beds, 10 to 60 cm thick, of lime floatstone and rudstone. In the thicker beds, the floatstone and rudstone consist of thin platy intraclasts of laminated, dolomitic lime mudstone, 1 by 10 cm in size. The intraclasts are arranged in edgewise clusters or lie flat to imbricated in the pebble rock. Large trilobite fragments occur between the clasts; sand-sized intraclasts, skeletal remains and carbonate mud fills the interstices. Fissures, 10 cm wide and trending 072°, cut mottled lime wackestones and mudstones containing lenses of rudstone that lie close to the main rudstone beds.

*c) Upper Dolostone Member.* Dolostones of the upper part of the formation (belonging to the upper dolostone and cherty dolomite members of the Dolomite formation of Knight, 1980) are not well exposed in the area. However, there appears to be a number of yellow-weathering, thin to thickly bedded, pale grey dolostones that would correlate with the upper dolostone member. The dolostones show a variety of sedimentary structures including mottled, beds, flat planar lamination, small-scale crosslamination and crossbedding and some stromatolites. Mudcracks and fenestra occur in the planar-laminated dolostones and channels filled by cross strata cut into the dolostones. Crossbedded dolomitic grainstones, composed of rounded intraclasts, ooids, rare skeletal fragments and very well-rounded quartz sand grains occur on the north shore of Middle Pond. Mudcracked, dolomite mudstone drapes occur in the grainstone.

*d) Cherty Dolostone Member.* Rocks belonging to the cherty dolostone member, consist of thick beds of grey to blue-grey, finely crystalline stromatolitic and bioturbated dolostone and pale-grey dolostone similar to those of the rest of the formation. Chert is a common component of this upper member, which is about 180 m thick. They are best exposed in South Cove (Castors River map sheet), immediately east of the Whale Factory Pond fault on the north shore of Hawkes Bay and south of Hawkes Bay in quarry exposures that occur along an old woods road that branches off the now disused loop of Route 73 toward Bryants Raft Pond. Beds of cherty, oolitic dolarenite are intercalated with thin-bedded, burrowed dolostones and laminated and cryptalgal dolostone beneath the Watts Bight Formation in a roadside quarry 1.5 km west of Three Mile Pond (Castors River map area).

### *Age*

Trilobites including *Arapahoia* and *Blountia* were recovered from the prominent intraclastic lime rudstone at the top of the exposed section on the south shore of Hawkes Bay. *Dicellomus*, an inarticulate brachiopod, occurs in the basal shales and dolostones along the north-trending woods road in the southeast corner of the Port Saunders map sheet. Other inarticulate brachiopods, *Paterina*, *Obolella* and *Lingulella* were found in dolomitic lime mudstones in the middle stromatolite member on the north shore of Hawkes Bay. A primitive, open-coiled gastropod was found on the woods road between Bryants Raft Pond and Forked Feeder Pond (Port Saunders map sheet). The trilobites and inarticulate brachiopod confirm an early Late Cambrian age

for the lower part of the formation. The trilobites belong to the *Cedaria* or *Crepicephalus* Zone.

*Depositional Environment*

The rocks of the Petit Jardin Formation are full of rock and sedimentary structures that suggest sedimentation in a shoreline setting that included high-energy stromatolite build-ups and oolitic sands and more commonly, low-energy, intertidal muddy carbonate flats.

However, the changing succession through each member suggests the exact shoreline setting varied with time. Since the character of the members in the map area appears to compare favourably with that of equivalent members farther north on the Northern Peninsula (Knight, 1977, 1978, 1980), this variation may well reflect regional changes of sedimentation style on the Late Cambrian shelf, rather than shifting facies belts migrating back and forth over the shelf.

The extensively mudcracked shales and thinly bedded dolostones, exhibiting fenestra, cryptalgal lamination and small-scale ripple marks having desiccated 'pans' of algal mat, characterize the lower member. These features suggest the lower member was deposited in a low-energy, low-gradient, wide tidal flat that occupied the high intertidal and supratidal zone similiar to rocks at the top of the underlying March Point Formation. Hypersalinity restricted shelly or burrowing faunas to rare inarticulate brachiopods and a few sparsely burrowed mud beds. However, there is no evidence of evaporitic minerals to suggest a true sabkha. The multicoloured shales probably accumulated in shallow, ponded-water bodies that were flanked by algal mats. High evaporation rates encouraged extensive desiccation and lithification of the mats with structures comparable to those described in sediments of peritidal settings and saline ponds of south Australia (Walter *et al.*, 1973; von der Borch *et al.*, 1977; von der Borch and Lock, 1979; Muir *et al.*, 1980; Ferguson *et al.*, 1982; Warren, 1982).

By contrast, mounded stromatolites, oolitic grainstones and intraformational breccias are interspersed with thinly bedded dolostones in the middle stromatolite member. Mudcracks, flaser-bedding, wavy lamination, small-scale crosslamination in the thin-bedded dolostones are characteristic of intertidal flats. Thin storm layers of ripple-marked, oolitic grainstone were washed onto the flats from oolitic sand bodies that formed in more open, high-energy settings. In some instances, the ooid sands are associated with stromatolites that formed narrow to broad zones of mounds that were flanked by or subsequently submerged by the oolite sands. Cross-stratification plus rip-up clasts of various origins suggest the ooid sands were deposited by storm-induced waves or tidal currents with sufficient energy to erode previously lithified crusts.

In modern and Holocene settings, oolitic grainstones form in both shallow sublittoral and intertidal settings. In Shark Bay, Australia, oolite sands form sublittorally, near exposed promontories and as elongate ribbons in embayments of an unprotected shoreline. Ooids swept by storms from these settings also contribute to adjacent high intertidal beach ridges (Hagan and Logan, 1974). In the Persian Gulf and locally along the western margin of Tongue of the Ocean, the Bahama Banks, oolite sands form in, and adjacent to, tidal channels between barrier islands. In some instances, oolites are moved landward onto intertidal sand bodies adjacent to the tidal channels (Newell and Rigby, 1957).

Mudcracked dolomite mudstone drapes, and layers in the oolite grainstone of the middle member, suggest that the grainy rocks were deposited as intertidal sand bodies. Rip-up intraclasts of oolite and dolostone imply early lithification also occurred. Fibrous to bladed-fibrous fringe cements in open spaces in the sands may have formed intertidally similar to modern beach rock cements (Scholle, 1978; Inden and Moore, 1983; Flügel, 1983) or within a marine or mixed-phreatic environment (Longman, 1980; James and Choquette, 1983) possibly in subtidal fringes of the ooid sandbodies.

The presence of a prominent inner zone of radial structure in the ooids suggests they may have formed in hypersaline water conditions (Halley, 1977; Flügel, 1983). Relict concentric lamination in the outer part of this middle zone may suggest that the radial fabric is diagenetic. However, because good concentric lamination is present in the core and outer zones of the ooids and radial ooids are enclosed in intraclasts, it seems likely the radial fabric is original. The contrasting fabrics may reflect fluctuating salinity conditions. Dolomitization of the formation is almost ubiguitous, apart from this oolite- and stromatolite-bearing section. However, because the dolomite is very fine grained and preserves the finest fabrics including dololaminites, it is probably syngenetic (Friedman and Sanders, 1967). In general, early dolomitization of tidal-flat carbonates is facilitated by hypersalinity. But, because limestones are retained in this localized section, it might be concluded that this may also reflect variable salinities in the more open, higher energy shoreline envisaged for this particular part of the member.

The internal structure of stromatolite beds shows they formed in response to low- to moderate-energy conditions. Smooth, flat cryptalgal laminite indicates the proliferation of stratiform cryptalgal mats in low-energy, flat, sheltered areas of the intertidal zone (Hoffman, 1976a). Development of mounds composed of large, robust, laterally linked hemispheroids upon the smooth mat suggests increased agitation and scouring in the intertidal zone. Delicate digitate structures composing mounds laterally equivalent of the robust build-ups probably formed in more sheltered, leeward areas of the cryptalgal barriers. The well-developed lamination in many of the mound beds supports their construction by smooth or colloform mats such as inhabit subtidal or lower intertidal zones of the Holocene embayments of Shark Bay, Australia (Logan *et al.*, 1974; Hoffman, 1976a; Playford and Cockbain, 1976). The discontinuous, wrinkled lamination of other mounds may be pustular mat more typical of higher intertidal settings (Hoffman, 1976a); mudcracked dolostones surrounding these mounds supports this conclusion (see Figure 6).

Thick, scour-based beds of intraclastic floatstone are interbedded with intertidal dolostones and grainstone sheet sands in the highest exposed part of the middle member. These deposits, composed essentially of laminated lime mudstone intraclasts, suggest they were derived by rip-up of thinly bedded tidal-flat carbonate, which perhaps had been previously lithified and desiccated. Abundant trilobite skeletal remains in the breccias suggest they may have formed close to the seaward margin of the tidal flats or perhaps were laid down sublittorally. Possible tidal flat depositional settings might include low-intertidal channels or high-intertidal storm-deposited gravel ridges (Shinn, 1983; Hagan and Logan, 1974). The lack of an exposed contact with associated facies does not allow more detailed interpretation.

The rest of the formation is too poorly exposed to discuss depositional environments except very generally. Structures and rock types again suggest an intertidal-flat setting for the upper succession. Of importance are the presence of very well-rounded quartz grains of possible aeolian origin in some of the dolostones of the upper dolostone member. Thick bioturbated dolostone beds alternating with more typical tidal-flat dolostones and stromatolitic dolostones in the cherty dolostone member, suggest fluctuating subtidal to intertidal deposition characterized the youngest deposits of the formation.

# ORDOVICIAN CARBONATES

## St. George Group

Dolostones and limestones of Early to early Middle Ordovician age that conformably overlie the Cambrian carbonates are placed together in the St. George Group. Four formations occur in the map area; they include in ascending order, the Watts Bight, Boat Harbour, Catoche and Aguathuna formations. The subdivisions follow essentially those first defined and later informally named by Knight (1978, 1980) and published in Knight and James (1988).

### *Watts Bight Formation*

#### *Definition and Distribution*

The Watts Bight Formation consists of massive, thick-bedded, black to dark-grey, frequently cherty diagenetic dolostone having some pale-grey limestones and dolostones that are extensively brecciated at the top of the formation. The formation underlies an extensive area of low ground on the easternmost part of the New Ferolle Peninsula from South Cove to Bartletts Harbour and Castors River, and can be traced eastward to Three Mile Lake (St. John Island–NTS 121/14, Castors River–NTS 121/15 map areas). It also occupies the northern half of the Castor Point Peninsula (NTS 121/15). The formation occupies coastal and inland exposures to the north and south of Barr'd Harbour on the St. John Island map sheet. The formation is recognized for the first time in the Port Saunders map area (NTS 121/11), where it generally forms ridges that rise above adjacent low ground underlain by recessively weathering rocks of bounding rock units.

The formation conformably overlies dolostone of the Petit Jardin Formation. The contact is exposed on the south side of South Cove. There, tan-weathered, thick-bedded, black, medium crystalline dolostone of the Watts Bight Formation overlies a thinly bedded, mottled, grey, fine dolostone, which also defines the top of the Petit Jardin Formation elsewhere on the Great Northern Peninsula (Knight, 1977, 1978). On the north shore of Hawkes Bay, the basal contact is faulted out by the Whale Factory Pond fault. The upper contact is placed at the top of a commonly brecciated sequence of light-grey to white dolostone and limestone that contain large cryptalgal mounds surrounded by grainstones that outcrop along the shore south of Fish Point. The upper contact is located, although not exposed, near Castor Point, probably at Yellow Point near Bartletts Harbour and on a point west of Caribou Cove where it is gently warped around a series of broad southwestward-plunging folds. The upper contact is not exposed in the Port Saunders map area but is exposed along the shore south of Fish Point and on the north and east shore of Round Head Island on the St. John Island map sheet.

#### *Thickness*

The thickness of the formation in the map area is calculated at approximately 100 m between the basal contact at South Cove and the upper contact near Caribou Cove. However, generally gentle dips and frequent changes of dip and strike, make accurate thickness calculations difficult.

#### *Lithology*

The Watts Bight Formation is composed mostly of thick beds of blocky weathering, massive diagenetic dolostone. White to pale-grey limestone that are replaced by pale-grey to white diagenetic dolostones occur at the top of formation. This part of the formation is also extensively brecciated.

The massive dolostone commonly weathers black to tan grey and varies between black and dark grey on fresh fracture surfaces. The dolostones are commonly 'bituminous' and also contain stringers and concretions of white- to dark-weathering, dark-grey to black chert. In some instances, the silicification has been fabric-selective so that boundstone structures, burrows, intraclasts and oolites are preserved. Characteristic of the dolostones is a grey to white, fabric-selective mottling that gives the weathered surfaces a distinctive colour pattern. The light mottling is associated with fine, equigranular dolomite that replaced burrows or columnar structure in boundstones. The dolostone is generally tight but also exhibits good but variable porosity including fracture, channel, intercrystal, breccia and vug types (Choquette and Pray, 1970). Megapores and fracture porosity are commonly lined or partly lined by white sparry dolomite. Small- and large-size megapores may contain variable amounts of laminated, pink- to buff-weathering, geopetal, dolomitic mudstone.

*a) Dolostone.* Thick beds up to 3 m characterize the dolostones. Thrombolitic boundstone mounds (Plate 22) or massive to bedded dolostone exhibiting burrow mottling are contained by the thickest beds. More rarely, however, some

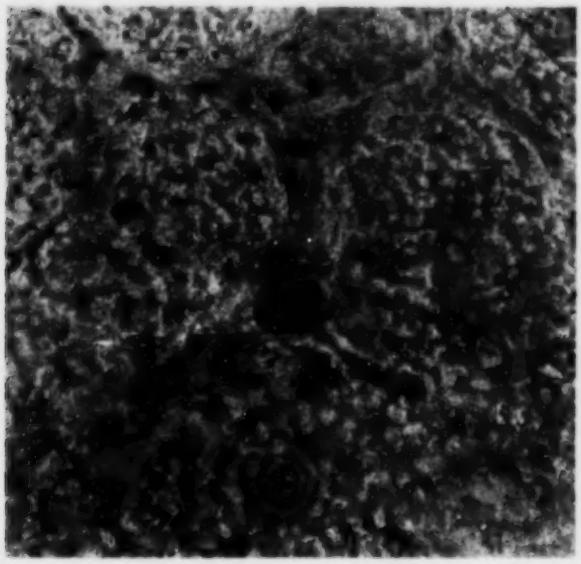


**Plate 22.** *Thrombolitic mounds in dark-grey, mottled Watts Bight dolostone; Barr'd Harbour.*

**Plate 23.** *Crossbedded dolostone of the Watts Bight Formation, north of Barr'd Harbour.*

dolostones exhibit trough crossbedding (Plate 23). Other dolostones, which are lighter in colour, are finely laminated, locally mudcracked and contain intraclastic layers. No sequential pattern of sedimentation is apparent in the dolostone. Boundstones occur in solitary mounds surrounded by bioturbated, thinly bedded dolostones or in extensive mound complexes that dominate many beds. Thinly stratified, bioturbated dolostone dominates one section of the formation for several metres near Barr'd Harbour. Bioturbated dolostone, overlain by stromatolitic boundstone mounds and in rare instances capped by light-grey, laminated, very fine dolostones, compose some 1- to 2-m-thick sequences. In other instances, bedded bioturbated dolostone intercalates at roughly 50 cm intervals with boundstone beds. Cross-stratification occurs in some dolostone beds, overlying and associated with mounds (Plate 24), near the top of the formation on the southern side of Castor Point Peninsula.

**Plate 24.** *Herringbone crossbedding in dolostone of the Watts Bight Formation, Castor Point Peninsula. Small cryptalgal mounds (arrows) form the base of the bed.*

Circular to spherical boundstone mounds, 0.6 to 1.5 m thick, and up to 1 by 3 m in diameter are common in both solitary and composite mound developments. Other cryptalgal deposits form very extensive banks composed of smaller heads.

Structure is not easily defined in the mounds. However, in cross-sections, some mounds display vertical, upward fanning and bush-like patterns of narrow, finger-like digitate structures that appear to lack any internal lamination, although this may have been obscured by dolomitization. Some mound complexes are composed of 15- to 30-cm-diameter heads, each outlined by a partition of dark-grey dolostone. Within each head, black and light-grey mottling on bedding surfaces produces a cerebroid pattern (Plate 22), again suggesting internal columnar structure. Where cross-sections of these heads occur, margins of heads are generally vertical. In others, the heads are upward expanding and globoidal in form, the heads apparently coalescing at the top. Internally, the dolomite mottling suggests a fan-shaped, bush-like structure of dendroid growth forms.

Porosity is high in the top of heads and brecciation in the outer margins of the heads is common. The spaces created in the outer rim of the heads and the interhead areas were filled by light-coloured, finely crystalline tight dolostone, locally displaying lamination. '*Conophyton* or *Jacutophyton*-like' structures (cf. Hofmann, 1969; Serebryakov, 1976) occur

with the other cryptalgal forms, generally clustered together or standing alone at the base of the mounds. The forms are 10 to 15 cm high, 2 to 6 cm in width and have vertical sides with a slightly thicker, bulbous top. Internally, the forms have an unstructured central axial zone surrounded by very fine, smooth lamination that parallels the shape of the structure in an outer zone, 1 cm thick.

Beds composed of stacked columnar hemispheroids and laterally linked hemispheroids are overlain by beds of laminated and mudcracked, light-grey dolostones. One such bed at Castor Point contains 10- to 20-cm-wide spherical heads composed of closely spaced, laterally linked hemispheroids and vertically stacked, dendroid columnar growth forms at the base. The heads are encrusted by dolostone composed of very fine black and white laminae (Plate 25). This laminite is widely but unevenly developed over much of the upper part of the bed where it encloses remnants of the stromatolitic dolostone. Cross-sections of the laminite reveal the white laminae are composed of fine, white sparry dolomite cements that have filled laminoid fenestral porosity. Black chert and pyrite occurs in the top of the bed, which is overlain by mudcracked, light-grey, dolostones.

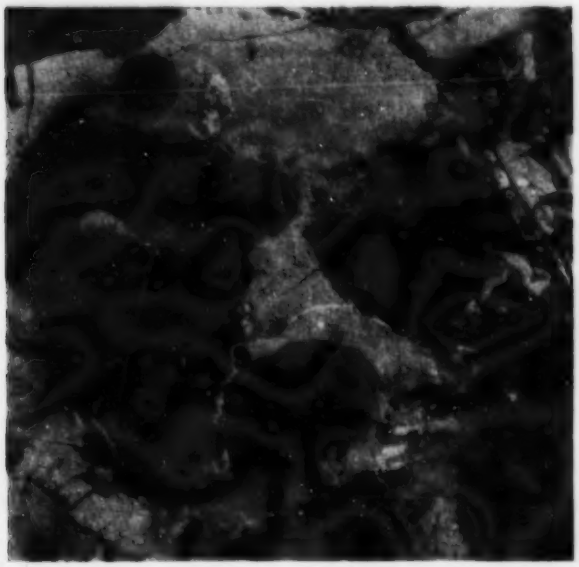


**Plate 25.** *Cryptalgal? heads composed of laminar, fenestral, dark-grey dolostone surrounded by mudcracked, buff-coloured dolostone, Watts Bight Formation, Castor Point Peninsula.*

The bioturbated dolostone of the Watts Bight Formation is characterized by planar to uneven thin bedding (Plate 26), or by more massive stratified dolostone that exhibits imperfect partings between sedimentary layers. Stratification is on a scale of 2 to 10 cm and bioturbation is intense to sparsely developed (Plate 27). *Planolites* sp. and a coarser branching burrow, possibly *Thalassinoides* sp., appear to be the dominant burrow forms (comparison with Kennedy, 1975; Frey and Howard, 1970).

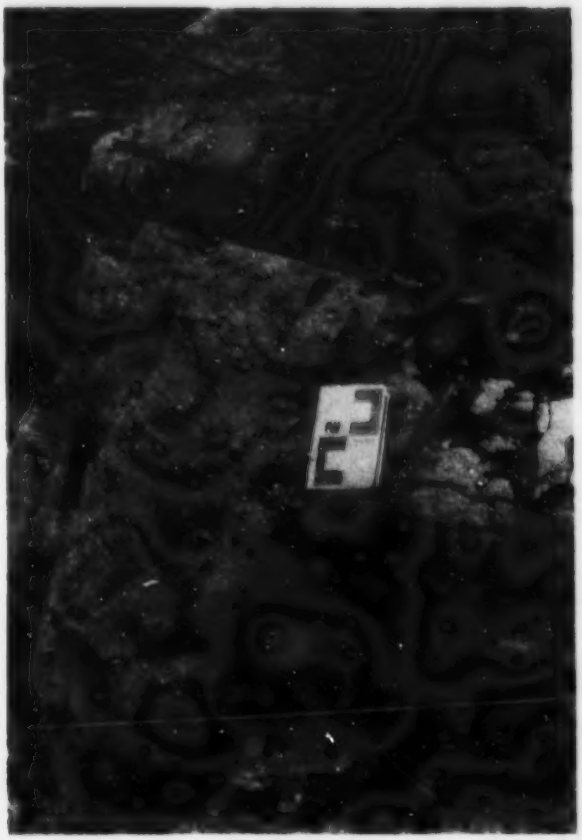


**Plate 26.** *Stratified bioturbated, dark-grey dolostone of the Watts Bight Formation, north of Barr'd Harbour.*

*b) Upper Limestone.* Large thrombolitic boundstone mounds, up to 60 cm high, occur in the white limestones of the upper 30 m of the formation. They are surrounded by thinly bedded intraclastic, skeletal, oncolitic packstone, which contains abundant gastropods, cyrtoconic cephalopods and trilobites.

Large oncoids up to 10 cm diameter occur in the grainy intermound fills (Plate 28). They consist of dark micropeloidal to dense microspar layers alternating with lighter microspar layers rich in fenestra and filled by clear blocky microspar. Some leached fossil fragments also occur in the structures.

The internal structure of the thrombolites consists of areas of micrite, micritic peloids and open spaces now filled by mosaic sparry cements. However, also present in the white limestone mounds are partly silicified remains of the coral Lichenaria. Small clots and protuberant areas of micrite, within spaces now closed by mosaic cements, suggest the calcareous microbial organism *Renalcis* may have significantly contributed to the mounds. Densely, interwoven spar-filled tubules reminiscent of *Girvanella* were also noted locally in thin section. Molds after skeletal fragments trapped

**Plate 27.** *Thick bed of burrow-mottled (arrow) Watts Bight dolostone, north shore of Hawkes Bay.*

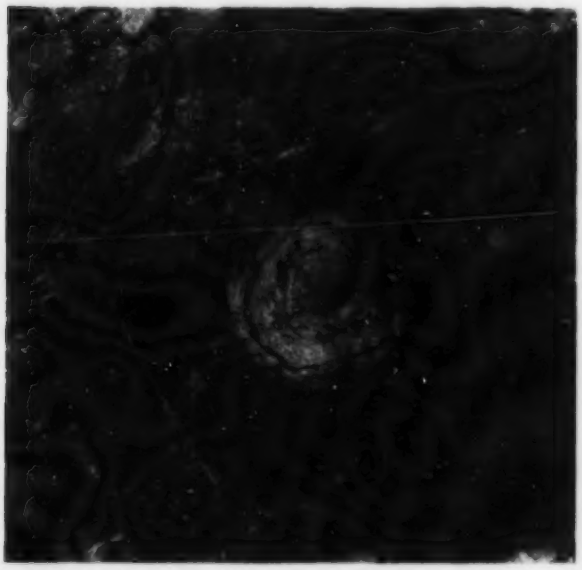


**Plate 28.** *Large oncolite in skeletal wackestone, which fill areas between mounds in a white limestone bed, uppermost strata of the Watts Bight Formation, Fish Point.*

in the mounds, are filled by mosaic sparry calcite. Similar thrombolites have been well described by Pratt and James (1982).

*Petrography of the Dolostones*

The dolostones are diagenetic dolomites (Friedman and Sanders, 1967), which have pervasively replaced boundstones and bioturbated limestones. The dolostones generally consist of equigranular, hypidiotopic dolomite crystals that vary in size between 200 and 300 μm. The crystals giving the dark colour to the rock are generally brownish in thin section, speckled, clouded and outlined by pyrite, hematite, limonite and amorphous iron oxides. Dolomite in burrows is generally clearer. Crystal zoning is common in some thin sections having a core of clear dolomite surrounded by the brown-tinted dolomite within rhombic crystals. Where these zoned crystals protrude into pore spaces, they are enlarged by an outer zone of clear spar. Stylolitic seams and contacts later reduce crystal size. Pores are generally filled by blocky, euhedral clear dolomite spars, 1 to 1.5 mm in size. Ghosts of fossil remains are rarely seen but, where present, clearly show an earlier replacement stage of inequigranular crystals, which possibly formed after shell leaching. This early dolomite was then overprinted by the later, cloudy hypidiotopic dolomite; the fossil shape and outline retained as a ghost within the crystals, even though the later dolomite crystals crosscut the shell.

In the boundstone and other dolostones, the crystal size is inequigranular and the crystal texture varies from idiotopic to xenotopic. Intercrystal porosity is variable in these dolostones.

Silicification in thin section can be seen to replace selective zones of dolomite, particularly at the edge of cryptalgal structures. The cryptocrystalline chert encloses, densely packed to scattered 30 to 50 μm, dolomite rhombs and grades into pervasive diagenetic dolomite at one contact but passes abruptly into the latter at the other. Rounded intraclasts preserved by the chert have ghost textures typical of peloid wackestone. These features suggest that the silicification occurred before the pervasive phase of dolomitization was initiated.

*Age*

The only fossil data available for the formation comes from the limestone at the top of the formation. Intraclastic, skeletal, oncolitic packstone close to thrombolite mounds yield the gastropods *Ecculiomphalus? atlantica* Billings, *Lecanospira? nerine* Billings, *Euconia* sp. cf. *E. beekmanensis* (Whitfield), *Lophospira* sp. cf. *L. calciferus* Whitfield (D. Boyce, personal communication, 1983). Also present are undetermined cyrtoconic cephalopods and trilobite fragments of *Parahystricurus* sp. I (Ross, 1951), *Paraplethopeltis seelyi* (Whitfield, 1889) and an undetermined species and genus. *Parahystricurus* sp. I occurs in Ross–Hintze Zone C in Utah and Nevada, suggesting a late Gasconadian age for the top of the Watts Bight Formation.

Conodonts recovered from the limestones include *'Oneotodus'* sp. A and a collection of new genera and species not known from platformal facies in Newfoundland (S. Stouge, personal communications, 1985). They belong to Stouge's (1982) Fauna 1 and suggest a midcontinent Fauna C correlation. Outside the area, conodonts (Stouge, 1982) and ellesmeroceratid cephalopods (Flower, 1978; D. Boyce, 1983b, personal communication, 1978) support a Gasconadian age for all or part of the formation.

*Depositional Environment*

Although the original carbonates of the Watts Bight Formation have been pervasively dolomitized on a regional scale, the preservation of depositional fabrics on an outcrop scale indicate that the strata were laid down in shallow shelf to intertidal settings.

The large boundstone mounds and mound complexes interbedded with, and surrounded by, burrow mottled dolostones are interpreted to have accumulated subtidally as earlier proposed by Knight (1977, 1978). The bush-like digitate structure and the cerebral fabrics in many of the mounds appear to lack internal lamination. This suggests that the mounds are thrombolites (Aitken, 1967), which are thought to develop in shallow subtidal conditions as well as in the lower part of the intertidal zone. A subtidal origin is supported by the presence of *'Conophyton* or *Jacutophyton*-like' stromatolites toward the base of some of the mounds (cf. Rezek, 1957; Hoffman, 1974; Donaldson, 1976). Similar *'Conophyton*-like' forms noted by Pratt and James (1982) were interpreted to have 'developed in lagoons protected from open subtidal areas by oolite or calcarenite bars'. However, the general lack of high-energy sand bodies in the associated section, and the importance of the bedded and extensively burrowed dolostone suggest that the thrombolites and *'Conophyton*-like' forms prospered in an open subtidal setting. Upon this shelf studded with mound complexes, more sheltered zones in mound complexes clearly could have suited the growth of the *'Conophyton*-like' forms. The importance of cryptalgal and cryptalgal–metazoan mounds as a major component of Late Cambrian to Early Ordovician shelf build-up is now widely recognized (Aitken, 1967; Toomey and Ham, 1967; Toomey, 1970; Ahr, 1971; Riding and Toomey, 1972; Knight, 1977; Toomey and Nitecki, 1979; Pratt and James, 1982). In Newfoundland, Pratt and James (1982) have described thrombolite–metazoan mounds consisting of thrombolites, *Renalcis* and the primitive coral *Lichenaria* at Green Head, Port au Port. This strata is believed to be laterally equivalent to part of the Watts Bight Formation. Dolomitization has obscured much of the fine detail in the Watts Bight mounds but the presence of complex gross morphology within cryptalgal structures suggests it is unwise to rule out the occurrence of thrombolite-calcified cyanobacteria–metazoan associations in the area.

However, the large thrombolite mounds preserved in pale-coloured limestone near the top of the formation contain *Renalis, Girvanella* and *Lichenaria* typical of Green Head mounds.

Extensive organic reworking of seafloor carbonates around and away from the mounds indicates a thriving soft bodied fauna inhabited the shelf. Gastropods and straight cephalopods were present in small numbers.

Where bioturbated dolostones and cryptalgal mounds built of stromatolites are interbedded with thinly bedded and laminated dolostones, the environment of deposition had shifted to include subtidal and intertidal deposition. Mudcracks in the bedded dolostones indicate subaerial exposure. Crossbedded dolostones suggest carbonate sand bodies developed locally to fringe the intertidal stromatolite build-ups.

## *Boat Harbour Formation*

*Definition and Distribution*

The map area contains, in the extensive coastal exposures that hug St. John Bay, one of the best exposed sections through the Boat Harbour Formation on the Great Northern Peninsula. The formation is a sequence of intercalated limestone and dolostone. The first 22 m consists mostly of thin-bedded dolostone and limestone with some stromatolite mounds and locally developed collapse breccias. This is overlain by cyclically developed grey limestone and buff-weathering, light-grey dolostone or dolomitic limestone in the rest of the formation. A disconformity occurs within 15 m of the top of the formation.

The formation underlies a southwest-trending strip of country west of the Ten Mile Lake fault in the vicinity of St. John Bay. The formation is well exposed along the shores of the bay from the south side of Castor Point and Squid Cove southwest to Old Man Cove and Hunters Point. The formation also underlies Keppel Point peninsula and much of the Saunders Point peninsula. It is well exposed on James and Fox islands (St. John Island map sheet). The youngest beds are exposed along the shore near Barbace Point but here they have been replaced by epigenetic? dolostone over much of the section. The top of the formation is also well exposed on Keppel Island and Savage Island on the Port Saunders map sheet. Inland, the formation is generally recessively weathered and poorly exposed. However, it can be examined along the Mooney forest access road near Bryant Raft Pond and Angle Pond (Port Saunders map sheet).

The Boat Harbour Formation conformably overlies the Watts Bight Formation. However, stratabound and stratiform dolomite and chert breccias are widely developed at and beneath the contact on Castor Point Peninsula, near Fish Point and on the northwest point of Round Head Island. This lead to the earlier suggestion that the contact is a disconformity on the Great Northern Peninsula (Knight, 1980b). However, at Bartletts Harbour, the contact is placed at a yellow-weathering, laminated dolostone that overlies Watts Bight dolostone. Similarly south of Fish Point (best section in the area), the formation commences with a bed, 26 cm thick, of planar laminated, mudcracked, buff-weathering dolostone that is overlain by burrow-mottled and laminated,

thinly bedded, grey dolostone that is locally brecciated. The buff-weathering dolostone overlies conformably brecciated and unbrecciated pale-grey cryptalgal dolostone and limestone of the Watts Bight Formation. Since stratigraphic conformity is the norm then it suggests that the widely developed breccias have a collapse origin, perhaps signifying a widely developed cavern system at the stratigraphic boundary. The upper contact is seen in several places such as Catoche Point, the east side of Barbace Cove, at Hunters Point, in a roadstone quarry 800 m south of Eddies Cove West and west of the Viking Highway, on Savage Island at the mouth of Back Arm, and on Keppel Island. At each of these localities, it is placed at the last thick bed of mudcracked laminated, dolomitic lime mudstone and below continuous well-bedded, rubbly weathering, skeletal limestones of the Catoche Formation.

The formation in the map area contains parts of Richardson's (*in* Logan, 1863) divisions E, F and G as described by Schuchert and Dunbar (1934). Woodard (1957) placed undivided strata from the formation in the St. George Group. Kluyver (1975) called the incomplete section on the northern shore of the Port au Choix Peninsula, the Barbace Point Formation. The name is not used here (see Knight and James, 1986). Pratt and James (1982) refer rocks of the unit to the Isthmus Bay Formation, which is defined on the Port au Port Peninsula. This name is not used on the Great Northern Peninsula where equivalent strata are divided into the Watts Bight Formation and the Boat Harbour Formation. The Boat Harbour Formation was first named the 'unnamed unit' by Knight (1978) but was later named after its type section at Boat Harbour (Knight, 1980b; Knight and James, 1988; see also Stouge, 1982).

*Thickness*

The Boat Harbour Formation is approximately 105 m thick, in the section measured along the shore near Old Man Cove from south of Fish Point to Hunters Point (St. John Island map sheet). Only the upper 50 m of the Boat Harbour Formation strata is exposed at Barbace Point. Other sections of the top 20 m of the formation are exposed on Keppel and Savage islands (Port Saunders map sheet).

*Lithology*

The Boat Harbour Formation is a sequence of peritidal limestone and syngenetic dolostone that range across a wide spectrum of textural types. These include boundstone mounds, thinly stratified lime mudstones and dolostones, bioturbated and grainy wackestones and packstones, sheets of skeletal, intraclastic and oolitic grainstones as well as intraformational lime conglomerates.

For the first 22 m of the formation, the limestones are extensively replaced by diagenetic and epigenetic dolostones and are brecciated (Plate 29). Nonetheless, the original rocks in this lower sequence suggest it contrasts markedly with the thick mound beds of the underlying Watts Bight Formation and is not essentially different from the overlying undolomitized section of the formation. It consists of grey limestones and dolostones composed of burrow-mottled, thin-bedded carbonate, stromatolitic boundstone associated with flaser-bedded and also with laminated and thin-bedded dolomitic lime mudstone or dolostone, in addition to rare beds of intraclastic rudstone and bioclastic oolitic grainstone.

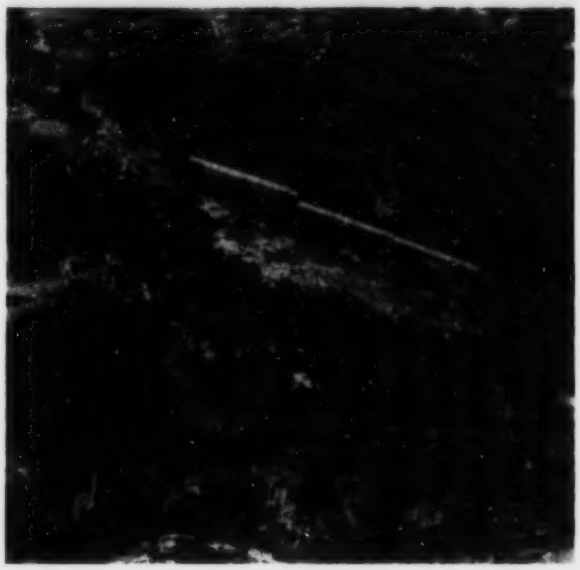


**Plate 29.** *Close up of collapse breccia showing dark dolostone clasts cemented by white sparry dolomite.*

Upward, the succession is composed mostly of 1- to 6-m-thick sequences of dark-grey, bioturbated wackestone–packstone overlain by buff-weathering, flaser-bedded and laminated dolostones and lime mudstone (Plate 30). Thrombolitic and stromatolitic boundstone mounds (Plate 31) and intraformational lime rudstone and oolitic grainstone beds also occur. However, in the transition from the brecciated–dolomitized base, up into the higher calcareous succession, there is a partly covered interval at least 14 m thick of grey, thinly bedded lime mudstone having shale drapes, partings and thin beds. Small (<10 cm in size) to large (60 cm diameter) boundstone mounds of irregular shape occur interbedded with the lime mudstones and scattered or nested together upon the bedding surfaces of the lime mudstones. This same succession occurs only a few metres above the base of the formation on Round Head Island, lying above the breccias described briefly above.

Twenty-four to thirty metres from the top of the formation, the succession is extensively dolomitized for some 1 to 20 m. This stratigraphic interval is mostly covered at Old Man Cove and is best exposed at Barbace Point. There, it contains two sequences hosting numerous quartz-lined vugs, and an irregular macrostylolitic surface, draped discontinuously with shale, occurs near the top of the second sequence. Thin-bedded mottled dolostones capped by two stromatolitic dolostone beds occur above. The top of the upper mound is cut by fissures and is affected by up to 25 cm of

**Plate 30.** *A shallowing-upward sequence in the Boat Harbour Formation, Eddies Cove West. It consists of bioturbated, dolomitic wackestone (lower arrow) overlain by flaser-bedded, dolomitic lime mudstone (middle arrow) and is capped by mudcracked dololaminite (upper arrow).*

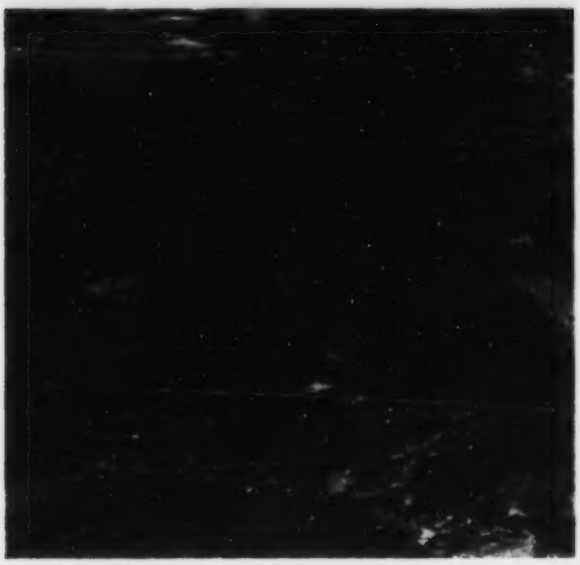


**Plate 31.** *Thrombolite mounds, surrounded by grainstone, lower member, Boat Harbour Formation, Eddies Cove West.*

brecciation (Plate 32); both fissures and breccia are cemented by dolomite enclosing rare chert sand grains.

This brecciated bed with the associated underlying dolomitization is believed to be stratigraphically equivalent of the 'pebble bed' and disconformity found at the formation type section near Boat Harbour (Knight, 1978). This is

**Plate 32.** *A layer of dolomitized rubble (upper arrow) resting upon a stromatolite bed, which is penetrated by rubble-filled fissures (lower arrow) at the Boat Harbour disconformity, Barbace Cove.*

strengthened by distinctly different trilobite and conodont faunas above and below the interval (Boyce, 1979, 1983; Stouge, 1982) and by the marked thickness and lithological similarity of rocks composing the top 17 to 20 m of the formation in sections within the map area. Laminated dolostones and lime mudstones, 1.5 m thick, overlie the covered interval at Old Man Cove, where they contain rounded to angular, white quartz nodules. Sitting upon the breccia at Barbace Point are 35 cm of parted dolomitic limestone overlain by 40 cm of skeletal wackestone containing trilobites, brachiopods and gastropods. However, striking in this uppermost interval of the formation are beds of ripple-marked and crossbedded, skeletal and intraclastic grainstone and rudstone (Plates 33 and 34) and flaser-bedded and laminated, shaly and dolomitic lime mudstones that are extensively mudcracked. The last 20 m of the formation is also markedly cyclical with sequences 0.40 to 2 m thick (see Figure 7 in pocket) composed of skeletal- and intraclast-rich packstones, bioturbated wackestones and lime mudstones in which skeletal wackestone lenses occur. No boundstones occur in this interval in the Eddies Cove West section but they are present in dolostones in the Savage Island and Barbace Point section as small heads and mounds, similar to the succession at the type section (Knight, 1977).

In faulted and folded, gently dipping strata south of Squid Cove, the stratigraphic succession of blue-grey limestone and pale-grey dolostone is poorly understood. However, in this coastal section along St. John Bay are gastropod-rich packstones, bioturbated wackestones, stromatolitic boundstones, and thin-bedded lime mudstones and dolostones. Extensive dolomitization and brecciation occur in the succession. One kilometre south of Squid Cove are strata, 2.39 m thick of pebbly and sandy, planar-bedded dolostones.

**Plate 33.** *Long linear ripple marks on the top of a grainstone bed, Barbace Cove Member, Boat Harbour Formation, Hunters Point.*

**Plate 34.** *Ribbon limestone (wackestone) showing shaly partings interbedded with erosive sheets of crossbedded, intraclastic–bioclastic rudstone (arrow). Barbace Cove Member, Boat Harbour Formation, Port au Choix.*

The sand grains and pebbles are up to 1 cm in size; they are composed of chert, dolomite mudstone and peloid dolomite wackestone. The chert grains are mostly structureless and composed of uniform finely crystalline and cryptocrystalline quartz; some rare grains, however, have preserved oolitic grainstone and peloidal packstone textures. The pebbles are scattered uniformly in a matrix of dolomite microspar and fine dolostone grains; chert cements some pores and later 150 μm dolomite rhombs extensively replace dolomite grains and matrix. In outcrop, the sandy dolostone displays planar bedding 5 to 10 cm thick; mudcracks were noted locally. The pebbly dolostone overlies a covered interval and is overlain by 1.87 m of cherty stromatolitic limestone, which passes laterally into stromatolitic and bioturbated, thinly bedded dolostone, which in turn passes laterally into a breccia. It is believed this sequence lies within the lower 30 to 50 m of the formation but the stratigraphic position is uncertain because of faulting of unknown magnitude and intermittent outcrop along the seashore of St. John Bay. It is thus possible that the pebble-sand bed is equivalent of the 'pebble bed' disconformity.

Five main lithofacies occur in the formation; they include (a) bioturbated lime wackestone, (b) lime packstone and grainstone, (c) lime mudstone and dolostone, (d) boundstone, and (e) exposure surfaces and sandy–pebbly dolostones. Although most of these facies are composed of limestone and are associated with selective dolomitization of thin layers or other fabrics, in some instances beds are completely dolomitized, but still show depositional fabrics and textures. In this report, no attempt is made to propose separate lithofacies or origins for such dolostones; rather the dolostones are viewed as dolomitized versions of the lithofacies described below. This is particularly so for dolostone beds that exhibit extensive bioturbation and flaser bedding. An exception are the dolostones of lithofacies C, which were deposited in a restricted supratidal environmental setting that facilitated early dolomitization that can be viewed essentially as syngenetic.

*a) Bioturbated Lime Wackestone Lithofacies.* This lithofacies, together with lithofacies C, dominates the formation in shoaling-upward sequences. The facies consists of 50 cm to greater than 100 cm beds of uneven and wavy, thin stratification and lenticular bedding, which is variably destroyed by sparse to common bioturbation (Plate 30). Lamination is observed in some less-burrowed thin beds. Thin beds and lenses of skeletal packstone and grainstone also occur. The burrows are commonly dolomitized, buff weathering and resistant on weathered surfaces. Deposits of intraclastic floatstone, a few centimetres thick, lie within or at the base of the facies. Gastropods and some trilobites, brachiopods and cephalopods have been noted in outcrop, crinoid fragments and calcified algal cysts in thin section. The wackestones in thin section reveal that they were originally composed of lime mudstone, peloidal wackestone and packstone and lesser peloidal grainstone layers that were subsequently admixed by the burrowing fauna. Peloids in layers where the peloids were closely spaced and cemented by interparticle microspar remain coherent; however, interlayered mudstone laminae appear to be composed of disintegrated peloids that give the mudstone a blotchy appearance in thin section.

*b) Lime Packstone and Grainstone Lithofacies.* Grainy beds, 10 to 50 cm thick, which locally lense out, are unevenly distributed in the formation. They include skeletal–intraclastic, skeletal–peloidal and skeletal grainstone and packstone and rare oolitic grainstone. The skeletal intraclastic

grainstone beds (Plates 33 and 34) are especially prominent above the disconformity at Eddies Cove West, Savage Island and Barbace Point. In these sections they are interbedded with 15 to 30 cm beds of wavy to planar-thin-bedded, frequently bioturbated, mudstones or wackestones, which resemble parted limestones of Aitken (1966). Grainstones are infrequent below the disconformity where they mostly occur as lenses within lithofacies A. Only three beds of oolitic grainstone were observed in the formation. They occur within the lower succession on the shore midway between Eddies Cove West and Fish Point.

The skeletal and intraclastic grainstones commonly have a planar to uneven scour base. Tops of many grainstone beds carry large, sinuous and straight ripple marks (Plate 33) having, in some instances, crests and enclosed intraclasts planed off as shown by overlying mud drapes. Ripple heights of 5 to 10 cm and wavelengths of 15 to 50 cm occur. Internally, the thicker beds are crossbedded with disc-shaped intraclasts and platy fossil remains lying parallel to foresets, which at intervals also have mudstone drapes. Run-off channels (guttercasts), a few centimetres deep and wide, cut obliquely across ripple marks on some surfaces at both Barbace and Hunters points. They are filled by lime mudstone, which also drapes over many rippled surfaces throughout the formation.

Grainy packstones mostly have uneven thin stratificaion with some crosslamination and lamination. Smaller ripple marks (including sinuous, rhomboid and ladder ripples) with heights of 0.5 to 1 cm and wavelengths of less than 10 cm characterize the packstones.

Skeletal components dominate the grainy beds. They include gastropods, small pelecypods, trilobite debris, smooth and ribbed brachiopods, ostracods and crinoidal material cemented by clear, mosaic spar. Intraclasts include dark-coloured peloidal wackestones and skeletal wackestones. There is extensive recrystallization and crinoidal fragments are enclosed syntaxically by large millimetre-scale calcite crystals.

However, before this coarse spar overprinted the grainy rocks, they were affected by early cements and shell modification. Dark micrite and wackestone having fine skeletal fragments filled the whorls and body chambers of many of the fossils before they were reworked and deposited in the grainstones. Gastropod and pelecypod shell structure are mostly neomorphosed to clear 10 $\mu$m microspar. Micrite envelopes outline some of the shells and in rare instances complete micritization of gastropod shells occurred. Edges of crinoid fragments are commonly degraded to micrite having micrite-filled microborings up to 30 $\mu$m deep into the grains. Brachiopods that are composed of robust, fibrous lamellar structure, and trilobites, show little or no alteration. Most grains following micritization were enclosed by a fringing blocky to radiating, bladed microspar cement. Remaining inter- and intra- particle pore space was closed by blocky mosaic calcite.

Peloidal grainstones tend to be sorted into size-graded laminae and the interparticle space cemented by 10 $\mu$m microspar. The peloids, which are generally 20 to 100 $\mu$m in size, are composed of dark micrite. Nonetheless, some grains in the peloid layers display a radial, spherulitic texture similar to the cocciod algae *Nuia*.

The oolitic grainstones occur in beds 20 to 30 cm thick composed of well-sorted, fine-grained ooids mixed with intraclasts and some skeletal remains. The latter include the gastropods *Raphistoma* sp. cf. *R. praevirum* Whitfield and *Murchisonia* sp. cf. *M. gracilens* Whitfield, undetermined ostracods, the articulate brachiopod *Diaphelasma* and the trilobite *Hystricurus oculilunatus* Ross (D. Boyce, personal communication, 1982, 1983). Intraclasts in the grainstone consist of oolitic grainstone composed of tightly packed smaller ooids in a micritic matrix. The oolitic grainstones have planar bases, flat thin internal stratification and planar- and ripple-marked tops, and are partly silicified. In the upper bed, ooid structure is obliterated by diagenesis, the cores of the ooids are extensively replaced by coarse spar and cortices by microspar; dolomite rhombs locally replace the cores of the ooids. In the lower bed, the ooids show a core of radial fibrous fabric beneath an outer cortex of one to several concentric laminae. Spar-filled tubular borings, filled by clear blocky microspar, penetrate some grains and small half-moon-shaped fenestra were noted within the outer rim of some concentric lamination.

*c) Lime Mudstone and Dolostone Lithofacies.* Mudstone beds of lithofacies C lie above bioturbated wackestones of lithofacies A or boundstone beds of lithofacies D, in sequences that shoal upward. The facies below the disconformity consists of dolomitic lime mudstone and dolostone and above of lime mudstone, dolomitic lime mudstone and shaly limestone and dolostone. The facies varies from 10 to 200 cm thick and is characterized by lenticular and flaser bedding (Plate 35), wavy to planar-thin bedding and lamination, some crosslamination, small-scale scour and fill structures, fenestra, small ripple marks and mudcracks. In general, flaser and wavy bedding that have minor bioturbated layers, hosting *Paleophycus* and *Chondrites* (Plates 36 and 37), occur immediately above facies A and complete many sequences. Mudcracks, ripple marks, smooth planar lamination and lenses and thin layers of intraclastic breccia associated with mudcracked surfaces occur toward the top of the facies units but are not exceptionally common. One facies unit midway through the lower member is a dololaminite of fine, planar lamination composed of calcic dolostone having minor lime mudstone laminae near the base and dolostone at the top. Slender, downward-tapering fissure cracks up to 15 cm in length, penetrate down through the dololaminite (Plate 38). Small mounds composed of clotted lime mudstone and intraclastic skeletal packstone are locally scattered upon bedding planes in the flaser-bedded variety of the facies (Plate 39). The intraclasts are derived from peloidal packstones that contain ostracod, trilobite and crinoid debris.

One dolostone bed near the base of the formation contains layers of small dolomite lined vugs (Plate 40). The nodular form of these vugs is similar to displacive nodular anhydrite. White cauliflower quartz nodules, and spherical, calcite-,

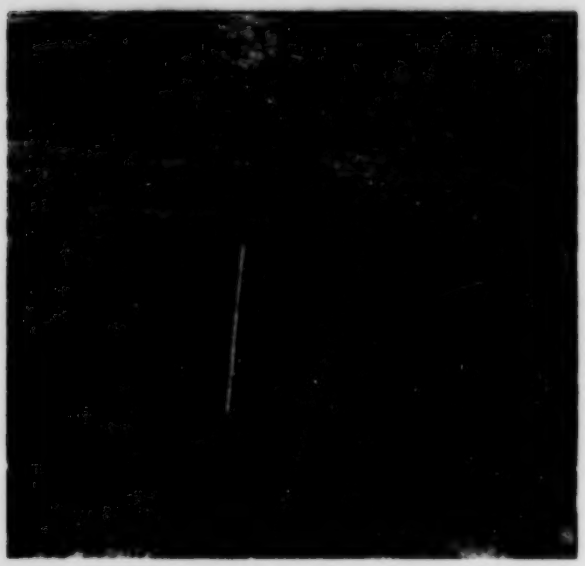


**Plate 35.** *Tidal-flat deposits of lenticular and flaser-bedded, dolomitic lime mudstone–wackestone at the top of a shallowing-upward sequence, lower member of the Boat Harbour Formation, just west of Eddies Cove West. They are overlain by subtidal–lower intertidal bioturbated wackestone of the next sequence (arrow).*

**Plate 36.** *Trace fossil* Chondrites *in dolomitic mudstone at the top part of a shallowing-upward sequence, lower Boat Harbour Formation, west of Eddies Cove West.*

ferruginous dolomite- and quartz-lined and filled vugs are common in the facies. Midway through the Eddies Cove West section, similar vugs in wavy-bedded dolostones include purple fluorite. In some instances, the vugs are clustered together giving a texture reminiscent of 'chicken-wire' texture of nodular anhydrite.

**Plate 37.** *Burrows in wackestone of the Barbace Cove Member, Boat Harbour Formation, Barbace Cove. The burrows are probably* Palaeophycus *sp.*

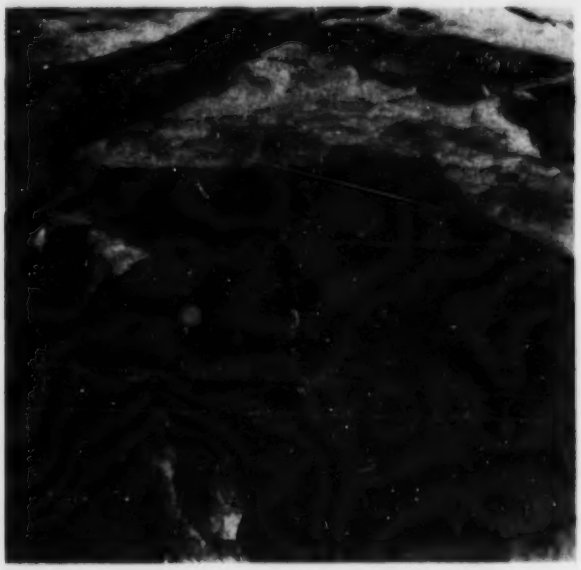


**Plate 38.** *Mudcracked, fissure-cracked (arrow) laminated, dolomitic lime mudstone and dololaminite.*

The lime mudstones consist of dark micrite having alternate laminations composed mostly of 20 to 60 μm dolomite rhombs. Dark carbonaceous, non-sutured stylolite seams occur toward the margins of the dolomitized laminae, and the rhombs are locally concentrated at the stylolite margin of the layer. Authigenic prismatic quartz also occurs in the micrite and dolostone.

Shaly lime mudstones of a slightly different character occur in the lower 23 m interval of the formation in the Eddies

**Plate 39.** *Numerous small conical, wackestone and intraclastic–skeletal mounds on the surface of bioturbated wackestone, lower member of the Boat Harbour Formation, Old Man Cove.*

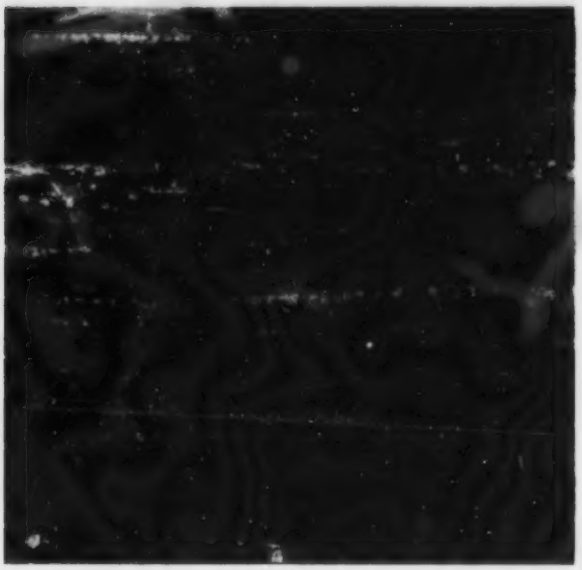


**Plate 40.** *Dolomite pseudomorphs after displacive anhydrite nodules and crystals in a thinly bedded dolostone, basal beds of the Boat Harbour Formation, Fish Point.*

Cove, West section. The lime mudstones are dull brown weathering, grey, thinly bedded, dolomitic and interbedded with grey shales. Locally, they are nodular; otherwise they are planar bedded having an abundance of bedding-plane structures, the most impressive of which are wrinkle marks, rill marks and oriented microfolded bedding (Plate 41). Mudcracks, small-scale ripple marks of <1 cm amplitude and a few centimetres wavelength, mudchip pavements having little or no re-orientation or transport of chips (Plate 41b) and intraclastic floatstone layers are also common. Irregular shaped cryptalgal mounds (Plate 41b) are interbedded at intervals in the mud rocks. The mudstones that overlie these mounds are brittly fractured in a distinct radial and concentric pattern reflecting compaction over the mounds. The subfacies is best seen in a cove 2.8 km north of Eddies Cove West but it has been observed, also, in outcrops 5.5 km north of Barr'd Harbour at the very edge of the St. John Island map sheet, and at the base of the formation on the northeastern point of Round Head Island.

*d) Boundstone Lithofacies.* Boundstones including thrombolitic and stromatolitic mounds, and cryptalgal laminites, are distributed uniformly through the lower member of Boat Harbour Formation although they only form 11 percent of the whole. Mounds in most of the member comprise grey to blue-black limestone. Cryptalgal laminites are best developed in shaly, pale-grey lime mudstones in the Barbace Cove Member 20 m of the formation, overlying the disconformity. They are described in lithofacies C above.

Individual boundstone mounds vary between 10 and 110 cm in thickness; sequences of two or more mound beds may dominate intervals up to 250 cm thick. The mounds, which can reach several metres in diameter have circular, spherical to irregular shapes having vertical to convexly curved margins. They are generally nested together in open banks in which individual mounds are generally surrounded by unevenly stratified and locally crossbedded, skeletal intraclastic packstones and grainstones. Mounds coalesce into linear biostromes in one bed midway through the Eddies Cove, West section (Plate 31) (Appendix 1, Section 4, Unit 46). The mounds are oriented roughly north–south (Figure 8).

The stromatolitic boundstone mounds are 10 to 35 cm in height and 10 to 60 cm in diameter. They are composed internally of widely to very closely spaced, columnar and bulbous structures, broad oblate hemispheroids of *'Collenia'* type and poorly developed, discontinuous, uneven flat lamination having abundant irregular fenestral porosity. The mounds are generally associated with lithofacies C dolostones. Just below the covered interval in the Eddies Cove, West section, stromatolite mounds occur together with thrombolitic mounds. The stromatolites include columnar-stacked as well as laterally linked hemispheroids, which microscopically consist of alternating laminae of dense micrite and fenestra-rich micrite. Thicker micrite laminae show a vague, clotted texture. Fenestra in the alternate laminae are tubular to irregular and branching in some laminae but flat and oriented parallel to lamination in others. The fenestra are filled by 0.01- to 0.1-mm-blocky spar. Irregular fractured walls of stromatolite columns are modified by vertical sutured stylolites. Intercolumn fill consists of micrite and micrite lithoclasts.

Vertically oriented, cylindrical to turbinate stromatolite growth forms, a few centimetres wide and several centimetres high, occur together in the thrombolite mounds of the same interval. The slender forms are composed of fine laminations

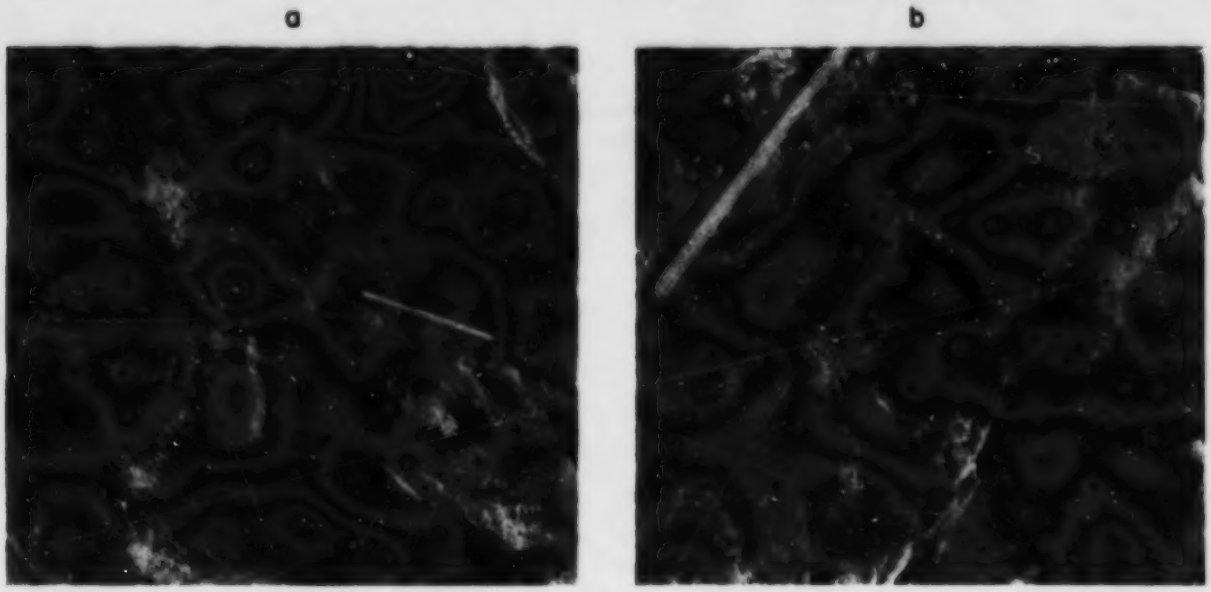



**Plate 41.** *Wrinkle marks and incipient* in situ *brecciation (a), and breccia pavements and small stromatolite mounds (S, in b) in cryptalgal lime mudstone facies, near the base of the lower member of the Boat Harbour Formation north of Eddie's Cove West.*

that parallel vertical to inflexed walls and continue over the slightly bulbous tops. This specific form was referred to as an 'aberrant' stromatolite by Pratt and James (1982). Intraclastic floatstones as well as skeletal and intraclastic grainstones are associated with the mounds. The mounds and intermound sediments are rich in the trilobites *Randaynia* and *Hillyardina* as well as gastropods.

Thrombolite mounds are best developed in Units 20, 27, 46, 61, 97 and 101 (Appendix 1, Section 4). For the most part, they consist of a clotted obscure texture, binding skeletal remains of trilobites and mollucses. However, Unit 46 consists of a basal foundation of intraclasts upon which a core zone of digitate structure, up to 40 cm high, developed. A millimeter-thick layer of chert seperates this core zone from an outer zone of irregular black to light-grey *Renalcis* clots and bushes. The *Renalcis* zone is up to 30 cm wide and completely enclosed the inner core. As a result, the *Renalcis* around the sides of the mounds constructed an open framework of rigid, irregular clots to gently inclined bushes. Buff-weathering dolostone of possible geopetal origin (locally it is laminated) infills the framework spaces. Very abundant *Lecanospira nerine*, a small gastropod, is bound by the thrombolite although locally they occur in cavities and occur as unbroken shells in fringing grainstones.

*e) Exposure Surfaces and Sandy–Pebbly Dolostones.* Approximately 13 m from the top of the Boat Harbour Formation is a surface of brecciation and silicification that is believed to represent an exposure surface. Also present are dolostones in which intraformational dolostone and quartz sand grains and pebbles are concentrated in thin beds or scattered on bedding planes. Location and description of these features have already been discussed (see Lithology Section, pages 39 and 40).

The sandy dolostone of Squid Cove possibly occurring low in the formation is composed mostly of cryptocrystalline chert and rarely of fibrous chalcedony. Most silica grains are internally structureless but some larger grains possess ooids and peloids cemented by dolomite and chert or chalcedony. Dolomite rhombs later grew in some of the chert grains. Dolostone pebbles in the beds consist of microcrystalline dolomite and equigranular, xeno- to hypidotopic dolomite. The silica and dolomite clasts are set in a microcrystalline ($<10$ μm) dolomite matrix, which is replaced by turbid to zoned (turbid core, clear rim), 150 μm rhombic dolomite crystals. Blocky dolomite of 0.25 to 1.5 mm crystals, fills fractures and locally replaces both matrix and grains adjacent to the fractures.

The main horizon that is believed to correlate with the 'pebble bed' of the Boat Harbour type area is exposed at Barbace Point. The horizon is a 15-cm-thick bed of breccia developed upon the top of a stromatolitic dolostone bed 38 to 66 cm thick (Plate 32). The bed is exposed over a strike length of at least 30 m on the west side of Barbace Point. The bed separates a succession of stromatolitic, bioturbated and wavy thin-bedded carbonates that are now almost exclusively dolomitized below from a succession of pristine limestone above. The limestones, which begin with wavy thin-bedded and laminated dolomitic lime mudstones having some fissure cracks, appear to lie conformably upon the breccia with no evidence of reworking of the rubble.

The breccia varies in its expression from north to south. In the north, the rubble is composed of breccia fragments,

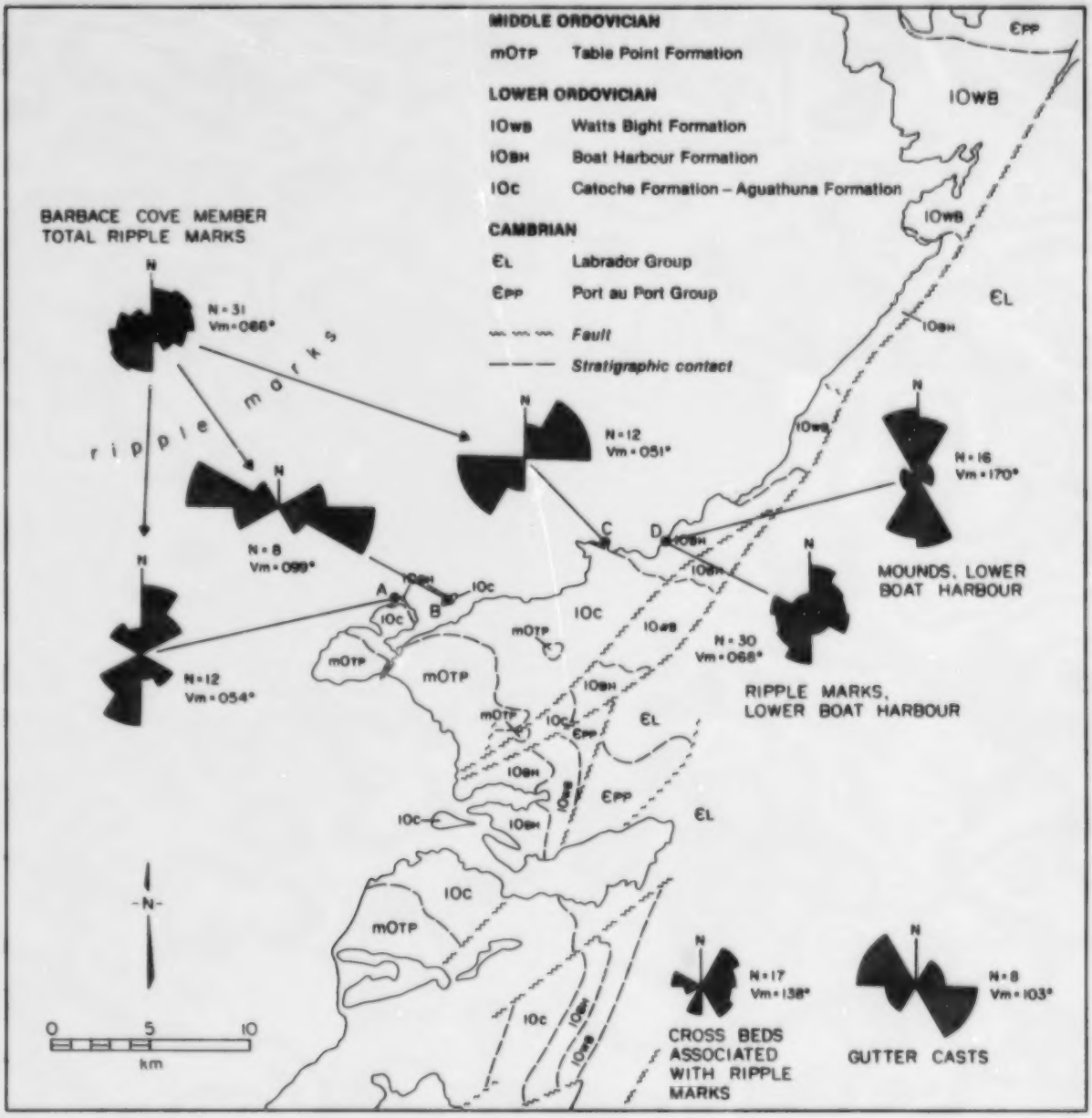



**Figure 8.** *Paleocurrents, Boat Harbour Formation; N = number of directions; Vm—vector mean; ripple marks represent direction parallel to crest. A—Barbace Point; B—Savage Island; C—Hunters Point; D—Eddies Cove West—Fish Point.*

1 to 5 cm in size of buff-weathering, laminated microcrystalline dolostone and dark-grey, finely crystalline dolostone. The clasts are embedded in a dark-grey, finely crystalline dolomite matrix and are cemented by white sparry dolomite and pale-yellow ferruginous dolomite. The white spar cement has replaced parts of the matrix dolomite, and many of the dolomite clasts, over large areas of the rubble zone. The presence of earlier clasts is supported by disoriented wisps of darker coloured dolomite that reveal the outline of the clasts. The microcrystalline clasts are apparently not effected by neomorphism and they locally appear to shield the matrix dolomite from alteration.

The breccia lies with an uneven base upon the stromatolites, truncating the top of mounds and locally thickening as downward projecting wedges into the underlying bed (Plate 32). This occurs particularly at the juncture of mounds and bedded sediments that fill the intermound areas. There is substantial porosity locally developed for up to 30 cm beneath the rubble in the stromatolite and intermound dolostone. Although most porosity of intra- and interparticle and fracture type is filled by white saddle dolomite, some open spaces at or just below the base of the breccia are filled by black finely crystalline dolomite (Plate 42). Open spaces including cavities, and extensive finer fabric-controlled porosity occur within underlying dolostone beds, particularly stromatolite mounds, for a few metres beneath the rubble bed. White saddle dolomite lines many cavities.

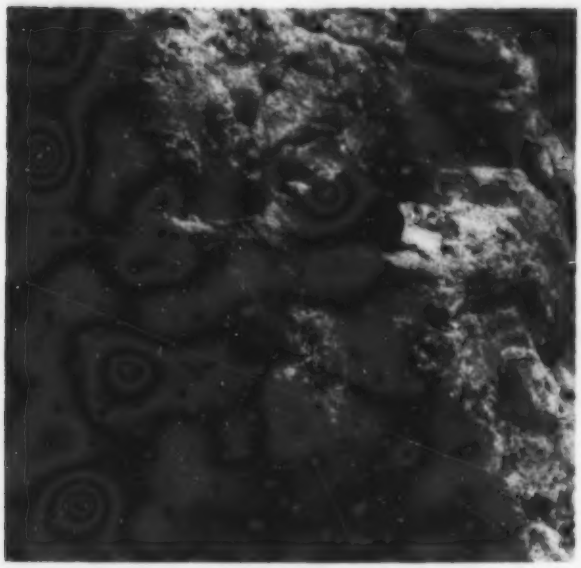


**Plate 42.** *Pockets of breccia (below lens cap), porosity and dark geopetal dolomite occur in the top of a stromatolitic dolostone just below the Boat Harbour disconformity, Barbace Cove.*

South of the outcrop, the breccia bed contains good angular clasts of dolostone and chert up to 10 cm in size set in a sparry dolomite cement. The clasts consist of structureless grey dolostone, laminated microcrystalline dolostone, and mottled, finely crystalline, dark-grey dolostone. Cross-sections of the bed locally show that there is a crude stratigraphy of dolostone fragments composed of alternating dark dolostone and laminated microcrystalline dolostone. Chert clasts also occur in rubble of the same area. They consist of off-white to black porcellaneus chert, chert exhibiting grainstone textures, white-zoned chalcedonic quartz and white megaquartz. Many fragments of the porcellaneus chert have at least one blackened edge, this colour variation clearly predating *in situ* brecciation of some chert clasts. Different orientation of the darkened edge from fragment to fragment reflects the final depositional attitude of each fragment. Elongate, wormy, white microcrystalline chert, possibly remnants of silicified burrows, also occurs as minor fragments.

Pyrite is also a common constituent of the breccia at the south end of the outcrop. It partly replaces and also coats dark-grey dolostone intraclasts. The white spar cement appears to replace the matrix and edges of some clasts in this area but not to the degree found at the northern end of the bed (Plate 43). Large cavity porosity that remained open after dolomite cementation was filled by a blocky calcite cement.

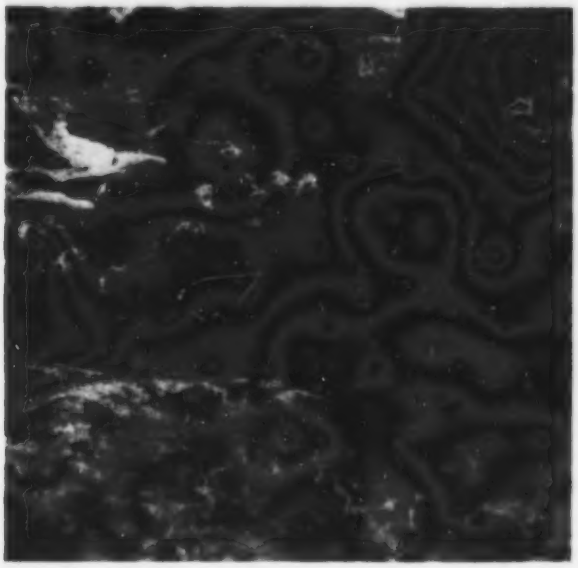


**Plate 43.** *Breccia of dolostone and chert lithoclasts lying upon dolomitized stromatolite at the Boat Harbour disconformity, Barbace Cove.*

*Paleocurrents*

Rose diagrams showing orientation of cryptalgal mounds, rill marks (gutter casts?), crests of ripple marks and crossbeds mostly associated with ripple marks are shown in Figure 8. The current directions are subdivided into those collected below and above the disconformity established 13 m from the top of the Boat Harbour Formation.

Below the disconformity, elongate mounds are north–south oriented having a mean trend of 170°. Crests of

ripple marks, which are generally of small size, show a strong northeast trend (mean of 068°) in a radial distribution. This northeast trend is more strongly pronounced in the total distribution of large sinuous ripple marks measured above the disconformity. There the mean crest trend is 066° but when this total distribution is broken down into the three collection localities at Hunters Point, Barbace Point and Savage Island, there is a variation of crest trends with means changing from 051° at Hunters Point to 099° on Savage Island. Nearly 50 percent of ripple crests lie within the 1 to 30° sector of the rose diagram in the Barbace Point station where the mean trend of ripple marks is 054°. Rill marks in the formation have a bipolar trend of 103°.

*Paleontology and Age*

Limestones of the Boat Harbour Formation in the map areas have yielded a diverse macro fauna that includes trilobites, gastropods, cephalopods, brachiopods, eocrinoids and ostracods as well as numerous conodonts. Of the main fossil groups, trilobites (Boyce, 1983a,b) and conodonts (Stouge, 1982; personal communication, 1984) are best known, and are listed in Table 2. Other fossils identified are also listed.

The fauna are divisible into two groups separated by the disconformity. Detailed analysis of this faunal break has been discussed for trilobites by Boyce (1983 a,b, 1989), and for conodonts by Stouge (1982). Below the break, dominantly hysticurid trilobites indicate a Ross–Hintze zone E to F age. These are associated with conodonts particularly *Macerodus dianae*, that Stouge (1982) informally called fauna 2 and is included within Midcontinent fauna D of Ethington and Clark (1971). Conodont fauna 1 is equivalent of midcontinent Fauna C (S. Stouge, personal communication, 1985). The gastropods *Lecanospira* and *Ecculiomphalus* characterizes the sub-disconformity fauna.

Above the disconformity, the trilobites *Isotoloides peri*, *Bolbocephalus convexus* and *Strigigenalis brevicaudata* appear to be the most common and widespread forms to occur, Boyce (1983a, 1985, 1989). Conodonts are also different and Stouge (1982) included them in fauna 3, which he believed still belonged to Midcontinent fauna D. The grainstones above the disconformity also contain numerous ostracods. The trilobites above the disconformity correlate with those of Ross–Hintze Zone $G_2$ (Boyce, 1983a) so that a hiatus spanning all of trilobite Zone $G_1$, and hence throughout much of the Jeffersonian, is likely. This suggests that the lower member of the Boat Harbour Formation was deposited in the Deminigian (late Tremadoc) whereas the upper member is of latest Jeffersonian (early Arenig) age (Boyce, 1983b).

*Secondary Dolostones and Breccias in the Watts Bight and Boat Harbour Formations*

*Description* The tan-grey, crystalline dolostones of the Watts Bight Formation in the map area are part of a regionally extensive unit underlying most of the autochthon on the Great Northern Peninsula, north of Daniel's Harbour. Characteristic of the dolostone is the preservation of depositional fabrics, generally uniform crystal size and generally restricted distribution of later generations of dolomite. Porosity although present is not very common and is rarely closed by coarse dolomite spar. 'Pseudobreccia' fabrics are rarely present.

In contrast, the secondary dolostones in the Boat Harbour Formation include more than one generation of dolomite. The dolostones, which are characteristically white to light, buff-weathering and pale-grey to white when fresh, are fine to medium in their crystallize. They may preserve sedimentary structures and locally small clots of limestone in which rhombic dolomite has grown. In more extreme cases, however, original textures are destroyed by pervasive dolomitization that produces thick beds of massive, light-coloured, crystalline dolomite shot through with clots and fractures of coarsely crystalline dolomite. An intermediate state is also common, producing a colour- and texture-striped rock composed of thin layers of early, fine dolomite separated by millimetre-thick layers of later, coarser, white sparry dolomite. Porosity within these secondary dolomites appears to be greatest close to the abrupt through uneven transition of dolomite into limestone; the vuggy dolostone at these junctures commonly weather with a honey colour similar to secondary dolomites extensively developed in the lower part of the Boat Harbour Formation elsewhere on the Great Northern Peninsula (Knight, 1978, 1980).

The secondary dolostones are light grey to white. They consist mostly of equigranular, hypidiotopic to xenotopic textures and have crystals clouded by inclusions. Later sparry dolomite consists of coarse, euhedral dolomite rhombs, which pervasively to sporadically replace the earlier dolomites. Unsutured clay seam stylolites and even laminar layers that result from pressure solution (Wanless, 1979) also occur in the dolomites.

Breccias (Plate 29) are extensively developed in the upper 30 m of the Watts Bight Formation in the Fish Point section, and at the base of the Boat Harbour Formation on the west side of Squid Cove, on the west side of Castor Point Peninsula, in strata north and west of Lossieux Point, Hawkes Bay, and on Round Head Island. The breccias consist of small to large angular dolostone fragments (maximum dimensions 1 by 1.5 m); chert fragments also occur. The dolostone fragments commonly show original sedimentary structures especially lamination and thin bedding. Others are of massive, fine crystalline dolostone; some blocks of the honey-colour weathering, porous dolostones also occur. The breccias at Fish Point are all cemented by a coarse, sparry dolomite (Plate 29) that rims fragments and closes off other open space. Most breccias are unsorted and unstratified. The breccias at Fish Point, however, have a bedded aspect, which suggests that there was no major displacement of dolostone beds during the brecciation process. Brecciation and dolomitization decreases upward in the lower 30 to 50 m of the formation.

Few contact relationships of breccia and bedded strata are exposed in the Fish Point area. However, bedded

**Table 2.** List of trilobites and conodonts recovered from the Boat Harbour Formation in the Port au Choix and Eddies Cove West areas. Trilobites (D. Boyce, personal communication, 1985); conodonts (Stouge, 1982)

TRILOBITES

Fauna Above Disconformity

*Ischyrotoma parallela* Boyce
*Benthamaspis hintzei* Boyce
*Isoteloides peri* Fortey
*Petigurus* sp. nov. A. Boyce
*Petigurus nero* (Billings)
*Bolbocephalus stevensi* Boyce
*Peltabellia* sp. cf. *P. willistoni* Lochman
*Peltabellia knighti* Boyce
*Bolbocephalus convexus* (Billings)
*Jeffersonia angustimarginata* Boyce
*Strigigenalis brevicaudata* Boyce

Fauna Below Disconformity

*Leiostegium proprium* Boyce
*Paraplethopeltis seelyi* (Whitfield)
*Hillyardina levis* Boyce
*Parahystricurus smithiae* Boyce
*Hystricurus deflectus* Heller
*Randaynia saundersi* Boyce
*Hystricurus oculilunatus* Ross
*?Paraplethopeltis* sp.
*Parahystricurus* sp. cf. *P. carinatus* Ross

CONODONTS

Fauna 3

*Ulrichodina* sp.
*Oneotodus costatus* Ethington and Brand
*Drepanodus parallelus* Branson and Mehl s.f.
*Scolopodus?* sp. C
*Oistodus inaequalis* Lindstrom s.f.
*Tropodus comptus* (Branson and Mehl)
*'Scolopodus' quadraplicatus* Branson and Mehl
*Drepanodus? gracilis* (Branson and Mehl)
*Acodus* sp. cf. *A. delicatus* Branson and Mehl
*Drepanodus simplex* Branson and Clark
*Acodus* sp. f. *A. deltatus* Lindstrom
*'Scolopodus' gracilis* Ethington and Clark
*Drepanodus suberectus* Branson and Mehl s.f.
*Scolopodus?* sp. A

Fauna Below Disconformity

Fauna 2

*Oistodus* sp. nov. B s.f.
*Oistodus* sp. nov. A s.f.
*'Scolopodus' gracilis* Ethington and Clark
*Drepanodus suberectus* Branson and Mehl s.f.
*Scolopodus?* sp. B
*Scolopodus?* sp. A
*Juanagnathus?* sp. A s.f.
*Drepanoistodus* sp. A s.f.
*Macerodus dianae* Fahraeus and Nowlan
*Scandodus* sp. A. s.f.

Fauna 1

*Scandodus* sp. A. s.f.
*?Oneotodus variabilis* Lindstrom s.f.
*'Oneotodus'* spp.

dolostones clearly pass laterally westward into and intertongue with the breccias. The dolostones can locally be traced eastward into pale-grey limestone beds.

At Squid Cove and on the west side of Castor Point Peninsula, breccias are extensively developed but clearly pass laterally into unbrecciated dolostone beds; vertical contacts of breccia and bedded dolostone (Plate 44) occur locally. The breccias on Castor Point Peninsula involve rocks of both the Boat Harbour and Watt Bight formations.

On Round Head Island, breccias are developed locally on the east side of the island as pockets, within limestones and dolostones, just above the basal contact of the Boat Harbour Formation. Overlooking Good Bay on the west shore, there is a breccia, which forms a linear body, up to 6 m thick, 3 to 25 m wide and at least 1 km long (Plate 45). A steep but irregular contact with gently eastward-dipping Boat Harbour dolostones occurs along the eastern side of the body. The rock breccia body trends about 060°. This is parallel to the main Acadian fault of the area, the Good Bay Fault. Subvertical joints and small faults, which cut the

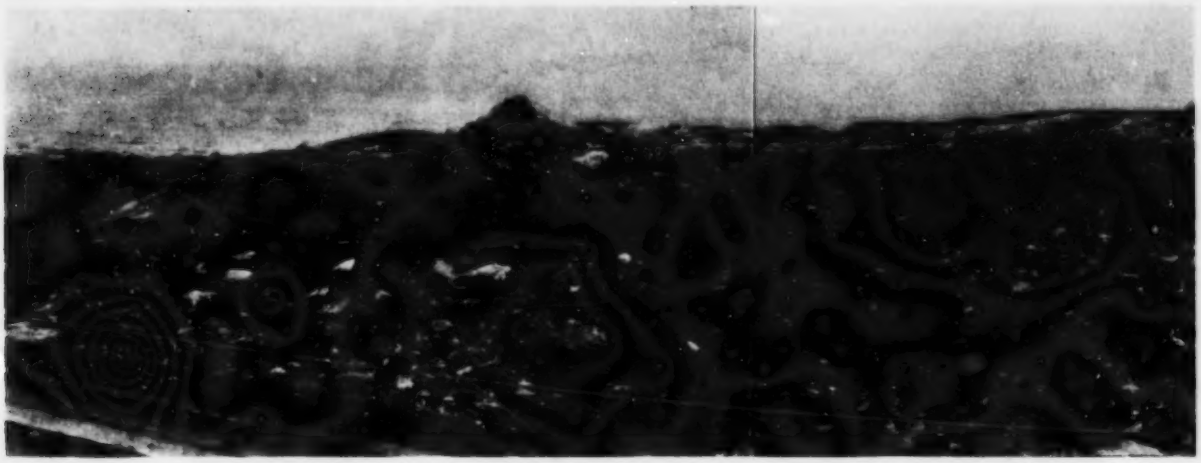


**Plate 44.** *Body of rock breccia abutting bedded dolostone (at arrow), base of Boat Harbour Formation, west side of Squid Cove.*

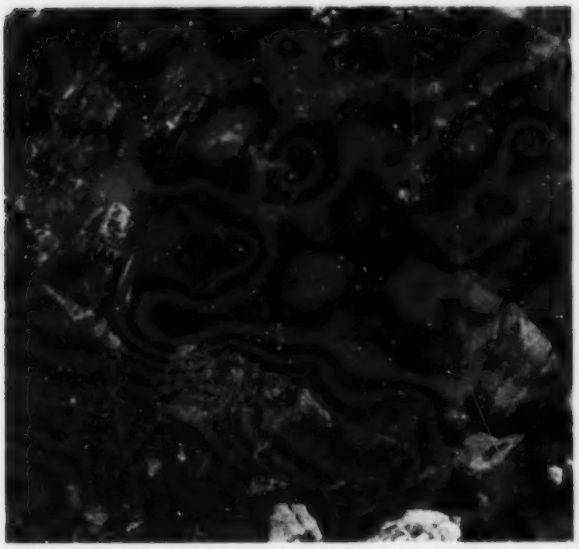


**Plate 45.** *Rock matrix breccia of large dolostone blocks set in a matrix of dolomite and of granule- and sand-sized clasts including rounded pebbles. Linear breccia at the base of the Boat Harbour Formation, Round Head Island, shore of Good Bay.*

breccia, also trend 060°. The breccia strikes southwestward into a topogaphic lineament (a saddle) and a shallow cove at the southwest end of the island. The shores of the cove are underlain by dolostones of the Watts Bight Formation. No brecciation and no obvious faults occur in the cove.

The western contact of the breccia is mostly eroded away but locally it is a subvertical fault of 060° trend and probably minor displacement. At the southern end of the breccia, Watts Bight dolostone lies to the west of and dips beneath the breccia. The breccia is composed of 30- to 40-cm-dolostone blocks, set in a matrix of silt- to gravel-sized dolomite and chert grains. Locally, rounded pebble-sized clasts occur in the matrices (Plate 45).

*Interpretation* The regionally extensive dolostones of the Watts Bight Formation, with their depositional fabrics preserved and general lack of multigeneration dolomite, suggest that the dolostones formed by pervasive replacement of a lithostratigraphic unit. This dolomitization was probably 'diagenetic' (Friedman and Sanders, 1967), and occurred most likely in the subsurface by replacement of a subtidal limestone unit during a single, time-bounded process. The stratigraphic location of the dolostones below a thick succession (100 m) of peritidal sediments of the Boat Harbour Formation may be critical to the dolomitization of the Watts Bight Formation. During the deposition of the Boat Harbour Formation, the shelf was essentially prograding, extremely shallow, and presumably having a landward margin exposed at the site of sandstone deposition (i.e., to the west). This allowed the introduction of freshwater into the subsurface, and the gradual migration eastward of a mixing zone of fresh and marine-pore fluids as the shelf prograded, which led to extensive mixing-zone dolomitization (Land, 1973; Morrow, 1982), within the Watts Bight Formation during deposition of the Boat Harbour Formation. Such dolomization is called 'eogenetic' dolomitization (Nichols and Silbering, 1980), and is interpreted to explain the common association of dolomitized subtidal limestone units beneath peritidal sediments and in some instances disconformities in the Great Basin of the United States (see also Dunham and Olson, 1980).

Dolomites in the lower part of the Boat Harbour Formation may be related to this process. However, multigeneration dolomites, presence of abundant porosity and special relationships to collapse breccias and faults, suggest it may include both mixing dolomite and later 'epigenetic' dolomites related to dolomitization along faults and fractures. Whereas the mixing zone dolomites would be Ordovician in age, the later 'epigenetic' dolomites would probably have formed in later Taconic (Middle Ordovician)

and perhaps younger Acadian (Silurian–Devonian) events. Evidence, which is reviewed further on, suggests that the breccias, although tectonically controlled, are Ordovician in age.

The Boat Harbour breccias are believed to be cavern breccias that developed close to faults, which penetrated through the carbonate platform, from the basement (cf. Lane, 1984). The consistent lithostratigraphic position of these breccias at the base of the formation also suggests a lithostratigraphic control.

The crude stratigraphy preserved within the breccias at Fish Point, the lateral passage of breccias into bedded dolostones and the vestiges of limestones preserved in the dolostones, suggest the breccias formed by dissolution of limestone beds and collapse of unsupported dolostone interbeds. There is no equivocal evidence in the Boat Harbour Formation of interbedded evaporite strata to suggest that collapse followed their dissolution. Minor features, such as white nodular chert and pseudomorphs after anhydrite, show that some evaporite minerals grew locally within the tidal-flat carbonates. Where contacts between the breccias and the dolostones are encountered, they are abrupt, irregular, vertically to steeply inclined as on Round Head Island and at Squid Cove and support the cavern breccia origin.

The linear breccia on the west side of Round Head Island provides the best evidence that there may be a structural control for these breccias. The steep contact along its southeast side and the lack of breccia developed in the underlying Watts Bight dolostones suggest a narrow northeast-trending body having little depth and variable width of 3 to 25 m. The body lies 300 m east of and trends parallel to the Good Bay Fault, an Acadian structure with vertical throw of 300 m. The breccia is cut by joints and small faults that are believed to relate to movements on the main fault. The presence of these fractures suggests that the breccias formed prior to Acadian deformation of the platform. However, since the breccia forms part of a northeast-trending lineament, it is tentatively suggested that the narrow breccia formed along essentially syndepositional fractures that penetrated upward from the basement into the Lower Ordovician platformal sequence (see also discussion of Aguathuna Formation). In general, there is a spacial relationship between the breccias and the major northeast-trending faults throughout the map area (see maps 91-173, 91-174 and 91-175 in back pocket). It is proposed here that it is the intersection of the fractures with this lithostratigraphic interval that controls the location of the breccias.

Some of the rock breccias have matrices of silt and sand- and gravel-sized clasts of country rock. At Round Head Island, rounded pebbles of chert and dolostone occur. Possibly, this matrix was washed into the cavity by subterranean streams and infiltrated the accumulating breccia. Alternatively, some of the caverns may have been open above to a subaerial exposure surface as for example, the disconformity near the top of the Boat Harbour Formation or the disconformity near or at the top of the St. George Group. Spaces between blocks that remained open near the top of caverns were later cemented by white saddle dolomite.

*Depositional Environment*

The rock types, sequences and sedimentary structures of the Boat Harbour Formation provide a classic example of peritidal sedimentation on the western Newfoundland platform during the Canadian. The 150-m-thick succession nowhere deviates from the peritidal model, composed of sequences that mostly compare to the shallowing-upward, low-energy intertidal muddy sequences of James (1984). The formation contains sequences of subtidal to intertidal mudrocks deposited in tidal-flat settings. Shallowing-upward sequences that also have cryptalgal mounds and lime sand deposits were laid down in somewhat higher energy shoreline settings.

Abundant carbonate mud and coarser particles including bioclasts, peloids and intraclasts were produced in the shallow-shelf sea. This provided detritus to nearshore subtidal areas leading to accretion of muds into the intertidal zone and to seaward-prograding tidal flats. A mobile and sedentary skeletal and soft-bodied burrowing fauna inhabited the shelf floor and muds in both shallow subtidal and intertidal settings.

The succession is broken by a disconformity surface 13 m from the top of the formation. This surface of suberial exposure is known to span much of the Jeffersonian (Boyce, 1983b). The carbonates beneath the surface were extensively dolomitized and silicified. Cavities and porosity were developed by dissolution in the vadose diagenetic environment. The exposure surface was also covered by a thin layer of rubble. Chert clasts in the rubble layer are derived from siliceous deposits that formed very early within the carbonates. They are the insoluble lag after dissolution of carbonates. However, the importance of chert in the carbonates immediately associated with the disconformity suggests that silica precipitation was genetically related to diagenetic processes in the thin rubbly soil zones of the karst surface.

Further discussion of the depositional environment logically falls into pre-karst (Demingian; late Tremadoc) and post-karst (latest Jeffersonian; earliest Arenig) settings since the two successions, although both peritidal, have contrasting characters.

Beneath the disconformity, the successions consist mostly of metre-thick sequences of burrowed, fossiliferous subtidal wackestones–packstones overlain by wavy, thin-bedded, lenticular- to flaser-bedded, sparsely fossiliferous and burrowed intertidal mudrocks. The environments are characterized by the fossil traces *Chrondrites*, *Paleophycus* and *Planolites*, which are common in modern and ancient carbonate flats, and shallow lagoon and shelf settings (Chamberlain, 1978; Narbonne 1984; Pickerill *et al.*, 1984). Mudcracks and desiccated dololaminite beds occur but are uncommon at the top of sequences. This suggests that high intertidal and supratidal subenvironments rarely developed.

Evidence for prolonged subaerial exposure of the tidal flats and development of localized karsts is not present.

Below the disconformity, several shallowing-upward sequences contain subtidal thrombolite and intertidal stromatolite mounds. The mounds, fringed by lime sands, perhaps formed at headlands or in channels, where tidal or wind-induced currents and waves locally produced suitably higher energy conditions. Boyce (1983a) has found that the mounds of the Boat Harbour Formation host their own ecologically controlled trilobite fauna. However, peculiar to the rocks, interpreted as tidal-flat deposits, is the apparent absence of channel deposits, which would be expected, as part of the tidal-flat model (Shinn, 1983). It is possible, however, that the deposits are not readily identifiable because the channels themselves were infilled mostly by muddy sediment that was also bioturbated.

The pre-karst succession is interpreted then as low-energy carbonate tidalite deposited by repeated lateral accretion of tidal-flat deposits over the shallow shelf. The paleogeographic configuration of the tidal flats is however, poorly understood at present. There is insufficient evidence available to know: 1) if the shelf was gently southeastward deepening with wide tidal-flat wedges building southeast from a shoreline to the northwest; 2) if during the Demingian epoch there was an outboard barrier complex to the southeast, behind which tidal flats might also have developed; 3) if active tectonism (fault-controlled uplift) on the platform produced highs around which tidal flats might have developed, or 4) was the shallow shelf, at this time, studded with numerous tidal-flat islands surrounded by subtidal deposits, as recently suggested for the Boat Harbour Formation by Pratt and James (1986) and for peritidal rocks, in general, by James (1984, page 225).

In the recent proposal of Pratt and James (1986), the interpretation of the rock sequences and facies of the Boat Harbour Formation, deposited in a shifting mosaic of tidal islands on the shallow Early Ordovician shelf, is partly modelled on modern carbonate mud islands of Florida Bay (Enos and Perkins, 1979). The attractive advantage of this model is that it allows the simultaneous accretion around the islands of many shallowing-upward sequences on the shelf. Consequently, each tidal-flat sequence is not required to prograde as a continuous belt across many tens to perhaps hundreds of kilometres of platform. The model may also explain the general absence of supratidal deposits and subaerial-exposure surfaces at the top of sequences and perhaps the absence of tidal channels.

On the steadily subsiding shallow shelf, sedimentation outpaced sea-level rise so that islands proliferated and enlarged upon the shelf. The supply of detritus diminished as the size of the offshore carbonate production area was reduced and possibly because the numerous islands obstructed the efficient movement of sediment to the accretionary centres. Subsidence then caused drowning of the islands. In this model, however, facies will pass laterally from supratidal to intertidal to subtidal over relatively short distances (James, 1984), a feature that is unlikely to be clearly demonstrated in the map area because of the lack of adjacent sections and the areally restricted outcrop in the lower member of the Boat Harbour Formation.

Current structures associated with the island model might be expected to be polymodal since the hydraulic regime would vary around each island. North–south orientation of algal mounds and dominantly northeast- to east-trending ripple crests were measured in the lower and upper sequences of the Boat Harbour Formation and also in the subtidal, open-shelf rocks of the overlying Catoche Formation. This suggests a stable paleoslope and paleoflow regime throughout the Early Ordovician. This may imply that an extensive tidal-flat wedge trending north to northeast, prograded from the shoreline to the northwest and/or southeast.

Following subaerial exposure of the platform, the Barbace Cove Member (the post-karst succession) formed the first deposits of renewed transgression upon the platform during the Arenig. Several sequences of shallow subtidal to muddy and grainy intertidal to supratidal limestones and dolostones lie above the Boat Harbour disconformity. The presence of fossiliferous, burrowed mudstones to packstones, several intraclastic–bioclastic grainstone beds hosting ripple marks and a number of beds of mudcracked, shaly dolomitic lime mudstones and cryptalgal laminites in these cycles suggest a dominantly muddy intertidal strandline that was influenced by storms. Coarse-grained storm layers were deposited together with muds in the intertidal zone, and rapid accretion of intertidal sediments facilitated the widespread development of supratidal flats.

Faunas in the mudrocks of this earliest phase of transgressive sedimentation differ from those below the Boat Harbour disconformity and are closely allied to those of the overlying Catoche Formation (Boyce, 1983b; personal communication, 1984). This suggests that these cyclic strandline deposits form the first deposits laid down during the initial stages of late Jeffersonian and Cassinian transgression of the platform, when sedimentation kept pace with sea-level rise. The nature of the sequences above the disconformity, the consistent northeast orientation of ripple crests and the laterally persistent stratigraphy of the Barbace Cove Member for tens of kilometres (underlying an area of more than 255 sq km) suggest these sequences formed in a wide tidal-flat facies belt and not a series of tidal-flat islands. The tidal-flat belt was rooted to the west upon the subaerially exposed platform, which was progressively overstepped, as sea level rise continued. The presence of storm-generated coarse, ripple-marked beds rich in fossil remains suggests an environment exposed to open marine influences.

### *Catoche Formation*

#### *Definition and Distribution*

Gently dipping bedrock along the shorelines of Bustard Cove and Port au Choix Peninsula provide excellent exposures of limestone and diagenetic dolostone that comprise the Catoche Formation. These sections reveal the formation as

a succession of rubbly weathering, well-bedded, fossiliferous, grey limestones overlain at the top of the formation by thick-bedded, massively weathering, dark-grey diagenetic dolostones. They have replaced the youngest limestones over a wide area of this part of the Great Northern Peninsula. Other good shoreline exposures occur along the south shore from Hawkes Harbour to Trappers Cove (Port Saunders map sheet). Away from the shoreline, exposure is poor; the formation occupies ridges that rise above low ground underlain by the recessively weathering Boat Harbour Formation.

The formation conformably overlies the Boat Harbour Formation (Plate 46). The basal contact is placed at the bottom of the first thick (60 to 100 cm) bed of rubbly weathering, grey limestone where it lies sharply upon a bed (20 to 50 cm thick) of mudcracked, laminated, dolomitic limestone. A 10- to 25-cm-thick bed of laminated limestone sits 60 cm above the base of the formation but rests within other limestones that have a Catoche aspect. The basal contact is well exposed at Hunters Point, the roadside quarry south of Eddies Cove West, on Savage and Keppel islands, Barbace Point, Catoche Point and on the south shore of Hawkes Harbour.

**Plate 46.** *Conformable basal contact of the Catoche Formation (at geologist's feet) upon the Boat Harbour Formation, Hunters Point, St. John Bay. Rubbly weathering fossiliferous Catoche limestone (with a sponge–thrombolite boundstone mound bed, arrow) overlies thinly stratified, laminated and mudcracked, dolomite lime mudstone of the Boat Harbour Formation.*

The upper contact of the formation is apparently conformable, although not well exposed on the east side of Back Arm, approximately 1 km northeast of the town of Port au Choix. It is placed at the top of the last bed of diagenetic dolostone where it is overlain by yellow-weathering, pale-grey, microcrystalline dolostone of the Aguathuna Formation. However, on the northwest shore of River of Ponds Lake, there is abundant evidence provided by an irregular surface cut in the diagenetic dolomite that a disconformity occurs at this contact.

The Catoche Formation was first named by Kluyver (1975) essentially for division H of Richardson (Logan, 1863). The type section is located along the Port au Choix Peninsula shoreline east and west of Barbace Cove continuing south to the cove of Port au Choix. Kluyver (*op cit.*) illustrated the section diagrammatically and it is unclear if his formation coincides with the present definition because the section on the Port au Choix Peninsula is faulted at critical points. Hence, it is recommended that the Bustard Cove section from Hunters Point, south 8 km to Back Arm, be adopted as the stratotype for the formation (see Knight and James, 1988). The Catoche Point section serves as a reference section and both sections and others in the formation are described in the appendix (see Appendix 1, Sections 5, 8 and 9) and illustrated in Figure 9.

The Catoche Formation is revised in this report following Knight and James (1988). Here it is enlarged to include the diagenetic dolostones that Kluyver (1975) placed in the Port au Choix Formation and that Knight (1977, 1978) referred to as 'Diagenetic carbonates'. These beds although extensively modified by dolomitization still retain sufficient character traits to suggest that the original limestones were in general like those of the Catoche Formation. This is supported by rafts of limestone preserved at the top of the formation type section at Back Arm and by dolomitic limestones that occur on a north-trending ridge, northeast of River of Ponds Lake (Port Saunders map sheet). These limestones apparently are not overlain by diagenetic dolostones but pass laterally both north and south into dolostones.

*Thickness*

The type section (Figure 9) from Hunters Point to Back Arm is approximately 160 m thick. This includes a major covered interval at the top of the limestone, which is calculated geometrically by ground measurements and independantly by structural cross-section, to be approximately 33 m thick. Outcrops along a nearby stream show the interval is underlain by limestone. The thickness of the limestone in the Port au Choix section is approximately 123 m overlain by 38 m of diagenetic dolostone south of Port au Choix cove. The diagenetic dolostone at Back Arm is 34 m thick.

*Lithology*

The Catoche Formation consists of a succession of buff- to grey-weathering, dark-grey limestone and white, brown to light-grey-weathering, dark-grey secondary dolostone. The limestone, which composes the lower 120 m of the formation, is rubbly weathering, well bedded, bioturbated and fossiliferous with sporadic moundstone beds (Plate 47). Dolomitic burrow mottling is ubiquitous. The diagenetic dolostone at the top of the formation is well bedded, massively weathering, fine to coarsely crystalline, bituminuous and possesses abundant open spaces and white sparry dolomite cements. Description of the dolostones of the Catoche Formation is discussed in detail by Haywick and James (1984).

**Plate 47.** *Typical well-bedded limestone of the Catoche Formation, Port au Choix Peninsula.*

**Plate 48.** *Interbedded pseudobreccia (white) and tight, grey, fine dolostone from the dolomitized top of the Catoche Formation, Back Arm.*

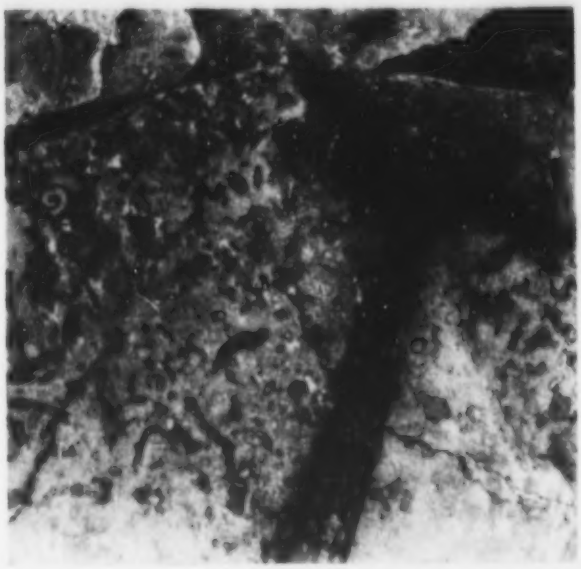


**Plate 49.** *Burrow mottling and ghosts of gastropods preserved in diagenetic dolostone at the top of the Catoche Formation, Back Arm.*

The limestone succession is fairly uniform consisting essentially of limestones that texturally vary from lime mudstone to grainstone. The muddy spectrum of textural classes (Dunham, 1962) dominate in the major beds. Grainstones generally occur as 5- to 10-cm-thick lenses and beds. In many instances they appear to form a capping layer to thick beds. Major undulose and planar scours that crosscut underlying stratification are common in the sections along Bustard Cove and at Catoche Point. Other facies that occur include cryptalgal boundstone mounds, flaser-bedded and laminated dolomitic limestones and rare intraclastic rudstones.

The top of the Catoche Formation is tan-grey to dark-grey, fine to coarsely crystalline dolostone that pervasively replaces the upper 30 to 40 cm of the formation. It forms alternating beds of tight, fine-grey dolomite and white, vuggy, coarsely crystalline dolomite (Plate 48) possibly reflecting an original cyclicity. Beds range from 0.6 to 3.0 m thick. Little of the original rock fabric is preserved but in some fine beds, vague planar to undulose thin stratification with subhorizontal burrows occur. Burrow-mottled dolomite and rare ghosts of gastropods occur in the centres of some beds (Plate 49). The vuggy dolomites contain abundant porosity, and veins and open-space filling of white saddle dolomite (Haywick and James, 1984). Irregular domains of dark dolomite are enclosed in the saddle dolomite giving the rock a brecciated appearance. Consequently, it was called 'pseudobreccia' (Cumming, 1968). Rafts of limestone occur near the top of the formation at Back Arm. Dolostones pass laterally into limestone containing gastropods and trilobites on a ridge just northeast of River of Ponds Lake.

*a) Bedded, Bioturbated Mudstone on Grainstone Lithofacies.* Lithofacies A dominates the Catoche Formation. Burrowing is ubiquitous and fossils common. Beds up to 1 m thick display planar to uneven, discontinuous, thin stratification composed of the different textural classes. Some mudstone layers retain lamination. The textural spectrum of the muddy rocks varies from lime mudstone with or without rare fossils, to peloidal-skeletal wackestone–packstone with some peloidal, or peloidal-skeletal grainstone. The lime mudstones consist of dark, structureless to blotchy micrite, which is variably recrystallized to 10 to 20 μm microspar. Moderately well sorted, micritic peloids, 0.1 to 0.4 mm in length, are

very common in wackestones. Rare spherulites, 0.4 to 0.75 mm in diameter, having a radial fibrous texture also occur. Microspar cements bioclasts and peloids in grainstone patches in the mudrocks. Skeletal remains in the mudrocks include eocrinoids, trilobites, brachiopods, gastropods and sponge spicules. Shell fabrics are frequently preserved in all but the gastropods, which were either leached and the mold filled by cement, or were recrystallized to clear mosaic spar. In some instances, the presence of gastropods is shown only by dark micrite and *Girvanella* and scattered 10 μm dolomite that filled the shell prior to its dissolution.

Burrows in the wackestones are filled by a loose to closely packed agglomeration of 100 to 200 μm anhedral to rhomboid dolomite crystals. Where dolomitization is incipient, the burrows are filled by 10 μm microspar and have a partial rim of dolomite apparently replacing, initially, the adjacent matrix and then the matrix and outer edge of the microspar in the burrow. The crystals are outlined by dark, ferruginous?, amorphous material. Some burrows are rimmed by 10 μm microspar betwen the micrite and the burrow dolomite and clusters of large barrel-shaped and prismatic crystals are attached to the burrow walls. Stylolites developed along the edges of dolomitized burrows and sutured stylolites have concentrated the burrow dolomite in irregular frayed, ropy seams so typical of this facies. Dolomite rhombs and microspar are digested along the sutures, which concentrate seams of amorphous ferruginous material that colours red and yellow under reflected light.

*b) Packstone and Grainstone Lithofacies.* The packstone–grainstone beds and lenses are commonly scour based and flat topped to ripple marked. Cross-stratification occurs with some of the ripple marks that are generally straight, sinuous to gently curved (especially when starved) (Plate 50). Ripple marks have wavelengths of 20 to 50 cm and ripple heights of 2 to 6 cm. Starved ripple marks are common. Crude planar, thin stratification occurs in other grainstones (Plate 51).

The grainstones and packstones are composed of bioclasts and intraclasts, or bioclasts and peloids. The bioclastic–peloidal types are well sorted with up to 80 percent peloids. Fine lamination and crosslamination are common and in beds composed of large 0.2- to 1.0-mm rounded peloids, good layer sorting occurs. *Girvanella* occurs in some peloids grains but most are uniformly structureless. Spherulites (possibly *Nuia*), 0.35 mm in size, are also present. Echinoderms, trilobites, gastropods (with whorls filled by dark micrite) and small ostracodes are the most common skeletal grains. Equant, 10 to 20 μm spar cements the grainstones; large single 75 μm crystals syntaxially enclose echinoderm platelets and poikiolitically several peloids. Small, 16 μm, very dark, dense peloids compose some very well-sorted grainy rocks, mixed with 50 percent, comminuted bioclasts up to 250 μm in size. Cement or matrix and locally fossils were recrystallized to 50 to 400 μm cloudy spar in this (laminated) grainstone.

The more common bioclastic–intraclastic grainstone and packstone are composed of mixed granule to small, pebble-sized lithoclasts and varying proportions of skeletal grains. The clasts consist mostly of lime mudstone and wackestone–packstone. Some lime mudstone clasts are structureless micrites, but others contain a few bioclasts and dolomite-filled burrows. The wackestone clasts include peloidal, spicular and bioclastic wackestone. Some peloidal wackestone clasts, composed of numerous 10-μm sized peloids, resemble the texture of cryptalgal boundstone (see below).

**Plate 50.** *A ripple-marked, grainstone lens, Catoche Formation, Port au Choix Peninsula.*

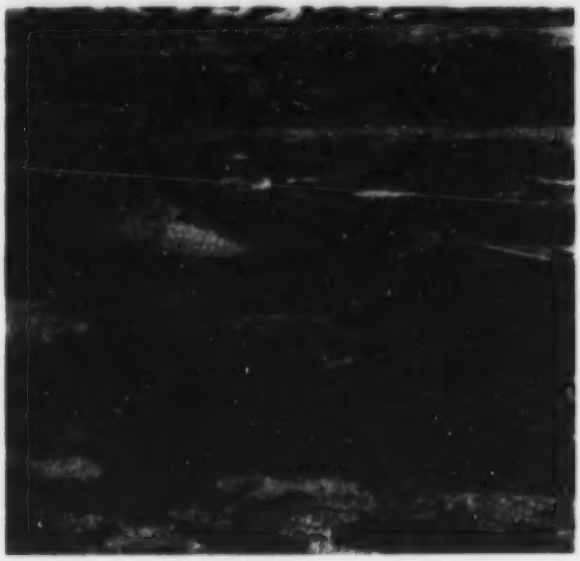


**Plate 51.** *Two lenses of rippled grainstone (arrows) lying above unevenly thin-bedded, burrowed, fossiliferous wackestone, Catoche Formation, Bustard Cove.*

Bioclasts of *Girvanella* and solenaporacean algae are present among the more typical gastropod, echinoderm,

brachiopod, and trilobite remains. Preservation and diagenesis parallels that of mudrocks in the facies. Shell fabrics of gastropods and cephalopods are lost to blocky mosaic cements that now preserve their presence. Dark micrite shell-cavity casts are the only evidence of the snails earlier presence. Similar dark mud is attached to brachiopod and trilobite bioclasts and was transported as coherent grains. Many bioclasts show a 10 to 20 $\mu$m micrite fringe.

The grainstones are cemented by anhedral, mosaic spar 10 to 50 $\mu$m in size. Small, 10 $\mu$m, bladed crystal pendants encrust sparsely the undersides of some bioclasts. Elongate bladed, radiaxial cement is clearly associated locally with shelter porosity, the crystals attaining lengths of 200 $\mu$m.

Micrite and microspar fill grain interstices in the packstones, which texturally resemble true grainstone. Local shelter porosity beneath bioclasts and peloids preserves bladed pendant and radiaxial fibrous cements. The remaining open space is filled by a clear blocky spar 0.2 to 0.5 mm in size.

*c) Laminated and Flaser-Bedded, Dolomitic Lime Mudstone and Wackestone Lithofacies.* Beds 20 to 60 cm thick of laminatd lime mudstone and shaly, wavy thin-bedded and flaser-bedded dolomitic lime mudstone (parted limestone of Aitken, 1966) occur in the basal 12 m of the formation and at scattered but rare intervals higher in the formation. One laminated lime mudstone, 22 m above the base of the Bustard Cove section, contains polygonal mudcracks. Higher in the formation, beds up to 35 cm thick of lime or dolomite burrow-mottled, massive dolostone or dolomitic lime wackestone overlie mound beds. The facies contains thin layers, 0.5 to 1.5 cm thick, of skeletal wackestone and packstone. Ostracodes are common and the facies has also yielded large fragments of the trilobite *Isotoloides* and graptolites including *Clonograptus* and *Dictyonema*.

*d) Intraclastic Rudstone Lithofacies.* Also present in the basal 12 m of the formation are beds of intraformational rudstone composed of rounded, discoidal, reddened, intraclasts of grey lime mudstone mixed with large cephalopods and gastropods and the trilobite *Isotoloides*. The beds are 15 to 40 cm thick and generally have scour bases, crude imbrication and locally edgewise orientation of clasts. Lenses and channelled deposits occur in Bustard Cove section (Unit 4d, Bustard Cove section, Appendix 1, Section 8).

The most impressive rudstone is found on Catoche Island of the Port au Choix section (Unit 4, Appendix 1, Section 9). The bed, 60 cm thick, can be traced across Barbace Cove where it is 30 to 35 cm thick (Unit 6, Barbace Point Section, Appendix 1, Section 6). The bed, which is cross-stratified (Plate 52), is composed of imbricated 1- to 2-cm mudstone pebbles. Bioclastic–intraclastic wackestone drapes, 1 to 7 cm thick, emphasize the large-scale, planar tabular, cross-stratification, which strikes 195 to 200° and dips 15° west-northwest. The mud drapes also show the unit to consist of 40- and 10-cm-thick cosets capped by a 10 cm bed of wackestone–packstone that fills the last shallow depression

**Plate 52.** *Tabular crossbedded rudstone that lies within stratified packstone and intercalated grainstone of the Catoche Formation, Catoche Island, Port au Choix Peninsula. The base of the rudstone is erosive. A layer of wackestone (compass rests on it) and imbricated intraclasts define the foresets of the large crossbeds.*

above the cross strata and below the sharp planar top. The rudstone grades upward from pebbles to granules. The rudstone rests with a planar, though locally erosive base, upon flat-bedded, bioturbated bioclastic wackestone.

Traced eastward along the outcrop, the thickest tabular cross-set is truncated by sets of trough crossbeds that are directed 288 to 328°. Overlying, the rudstone are two beds of intraclastic and bioclastic intraclastic grainstones that are not always visibly crossbedded but rather exhibit poorly developed planar stratification. Several other thin rudstone and grainstone beds (8 to 30 cm thick) interbedded with burrowed, thinly stratified wackestone occur in overlying strata.

In the section on the east side of Barbace Cove, the laterally equivalent bed is a scour-based, intraclastic rudstone. It is cross-stratified and intercalated with flaser-bedded dolomitic limestone and interlayered crosslaminated and laminated very fine-grained grainstone and wackestone. Upward in the section, the rudstones lie at the base of thick beds of typical bioturbated and fossiliferous Catoche limestone and in one instance show cross-stratification and ripple marks.

*e) Cryptalgal Boundstone Mound Lithofacies.* More common, and certainly striking, are beds of large boundstone mounds that are irregular, spherical and linear in shape. The first mound bed occurs 1 to 2 m above the base of the formation in each section measured on the western side of the Port Saunders map area (Figure 9; Plate 46). It is 50 to

60 cm thick and at Hawkes Harbour, it consists of two 55 cm beds surrounded by, and separated by, 12 cm of grainstone. The best development of this mound bed is found at Hunters Point where the mounds end at the southern margin of the outcrop. Here, they pass laterally into lime wackestone rich in *Ceratopea* and the rostroconch mollusc *Euchasma*. The mounds were also noted at the Boat Harbour–Catoche contact on Keppel Island.

Five additional mound beds, 0.4 to 1.2 m thick, occur within the basal 35 m of the section at Hawkes Harbour, and include two horizons of linear mounds. In the Bustard Cove and Catoche Point sections, mounds of similar dimensions occur mostly from 40 to 85 m above the base of the formation although small centimetre-sized mounds occur at the lower intervals. Linear mounds (Plate 53) occur 43 m above the base of the Bustard Cove section. Beds, 10 to 65 cm thick, of massive-weathering, lime-mottled dolostone or dolomitic wackestone overlie several of the mound horizons in the Catoche Point section. Large mounds occur in the eastern most exposures of the formation southeast of the Starvation Ridge fault near Forked Feeder Pond.

**Plate 53.** *Elongate boundstone mounds oriented north–south in the Catoche Formation stratotype section, Bustard Cove. A narrow grainstone fringe onlaps the mounds and burrowed, thin-bedded wackestone infills the rest of intermound zones.*

An abundant, large-sized fauna generally occurs with the mounds. Trumpet-shaped sponges (*Archeoscyphia*), plus sticks and tabular sponge fragments, receptaculitids (*Calathium*), straight to completely coiled cephalopods, high- and planispired gastropods, orthid brachiopods, eocrinoids and trilobites all occur within or marginal to the mounds. Slender, curving tubes, now composed of white calcite spar, are common on the mounds. They may be burrows or neomorphosed structures after an unknown organism. The eastern mounds at Forked Feeder Pond contain a parochial trilobite fauna characterized by the species *Illaenus* and a large, new species of *Bolbocephalus*. Grainstones and rudstones, which may be crudely stratified and crossbedded, fringe, intercalate, and surround the spherical- and irregular-shaped mounds. They also fill narrow intermound areas between clustered mounds; the grainstones are then mostly dolomitized. The linear mounds are associated with bioturbated and skeletal wackestones having very minor grainy carbonate.

The large mounds are steep sided, and 1 to 2 m in diameter. The linear mounds, which are oriented north–south and occur at Bustard Cove and Hawkes Harbour, measure up to 75 m in length, 6 m in width and have flat to irregular tops, and steep sides and tapering ends. They are seperated by 2- to 10-m-intermound lows filled by planar, thinly stratified, skeletal and bioturbated wackestone. Some ripple marks occur in the intermound areas, oriented perpendicular to the mounds. The tops of the Bustard Cove linear mounds are uneven with circular depressions up to 50 cm diameter filled by large gastropod and cephalopod shells. Polished outcrops of the linear mounds at Hawkes Harbour reveal that they are banks composed of clustered, circular thrombolitic mounds 55 cm in diameter.

The thrombolites consist of clots of micrite and microspar. The micrite is often dark and structureless but both the micrite and microspar show spar-filled *Girvanella* tubules, 10 to 20 μm in length and locally large 50- to 250-μm-blunt tubules (borings?). The 10 to 20 μm microspar is frequently cloudy and blotchy suggesting it replaces earlier micrite fabrics. In some instances, bush-like blotches reminiscent of *Renalcis* occur. Bioclasts are enclosed in both micrite and spar but many skeletal fragments are degraded unevenly to micrite for up to 60 to 100 μm around the shell margin.

Skeletal fragments, in particular gastropods, were neomorphosed or leached and the molds filled by microspar, after they were enveloped by a micritic fringe. Brachiopods, trilobites and eocrinoidal particles occur in the thrombolites. Sponge spicules and rectilinear cellular structures of sponges are preserved by clear microspar. Pratt and James (1982) have reported sponges, calcareous algae and the problematic organism *Pulchrilamina* from mounds in the Port au Choix section.

Open space in the thrombolites is filled by clear blocky spar. Some cavities are lined by radiaxial mosaic spar that rests on a substrata of 60 to 70 μm anhedral microspar containing blotches of micrite. Late dolomite rhombs replace both blocky and radiaxial cements.

*Paleocurrents*

Large linear cryptalgal–sponge mounds show a preferred north–south orientation (Figure 10). The mean bipolar trend is 013 to 193°. Small mounds show more variation, dominated by north–south-trending mounds; the mean trend is 127 to 307°.

The crest trends of more than 90 ripple marks were measured in the Bustard Cove, Catoche Point and Hawkes Harbour sections. Mean crest trends vary from 071 to 083° with a mean of the total directions at 077°. It is clear from the rose diagrams that nearly 50 percent of ripple crests trend north to northeast.

Orientation of straight, elongate cephalopods is also shown in Figure 10. The directions plot the expanding, open end of the fossils and show a radial distribution with most shells oriented by eastward-moving currents to give a vector mean of 137°.

*Paleontology and Age*

The Catoche Formation contains an abundant and diverse fauna listed in Table 3. Preliminary detailed studies of trilobites (Fortey, 1979; Boyce, 1979, 1983a,b, 1985, 1986 and in Stouge and Boyce, 1983) and conodonts by Stouge (1982) have occurred on the Port au Choix Peninsula. Boyce (1983a, 1986) has also collected from the Bustard Cove Section. A diverse trilobite fauna belonging to Ross–Hintze zones $G_2$ and H occur in the Catoche Formation of the map area (Fortey, 1979; Boyce, 1983a,b). Stouge (1982) has identified two conodont faunas, faunas 4 and 5, within the lower and upper part of the limestones of the Catoche Formation. Fauna 4 corresponds to Midcontinent Fauna E, and Fauna 5 is a transition from Fauna E of Ethington and Clark (1971) and Midcontinent Fauna 1 of Sweet *et al.* (1971).

Gastropods, particularly *Maclurites*, and cephalopods, of the *Cassinoceras wortheni* fauna (Flower, 1978) are also recovered from the formation in the map area. The graptolites *Clonograptus flexilis* (Hall), *Dictyonema*, and *Pseudophyllograptus* sp. A occur in the limestones of the Catoche Formation (Cumming, 1967; Williams *et al.*, 1987) in the Port au Choix section. These faunas each support a Cassinian (early Arenig) age for the Catoche Formation in the map area. The graptolites are indicative of *Tetragraptus approximatus* and *Tetragraptus akzharensis* zones (Williams *et al.*, 1987).

*Depositional Environment*

The Catoche Formation consists of a succession of dominantly open-shelf, subtidal limestones laid down during Arenig transgression of the Newfoundland platform. The first, peritidal limestones accumulated upon the tidal-flat sediments of Barbace Cove Member. Subtidal sponge-thrombolite mounds and bioturbated, fossiliferous mudrocks of the basal sequence are associated with intraclastic rudstones and grainstones, possibly storm-generated gravel bars and/or tidal-channel deposits, and with parted limestones and mudcracked, laminated mudstones that accumulated in tidal-flats.

Stratified limestones that are extensively bioturbated characterize the next 90 m of the formation. They were deposited in an open, subtidal, low-energy shelf setting that hosted a burrowing and diverse benthonic shelly fauna. Trilobite faunas include those evolved from inner shelf forms (Fortey, 1979; Boyce, 1983b; D. Boyce, personal communication, 1984) and some of deeper water affinity, which migrated onto the shelf as sea level rose and shelf waters deepened (Fortey, 1979, 1984). These forms, including *Carolinites* and *Opipeuter*, and the presence of graptolites suggested to Fortey (1979) that there was a connection between the open ocean and the shelf at this time.

Wave- or storm-generated bottom currents reworked and sorted sea-floor sediments and deposited the common, ripple-marked lenses and thin beds of bioclastic and intraclastic grainstone. Lithified intraclasts suggest sea-floor cementation and hardgrounds. Bottom sediments were extensively scoured during major storms when large crosscutting surfaces were excavated.

Boundstone mounds and mound banks composed of calcareous algae and sponges and a large-sized, shelly fauna flourished on the shelf periodically. The blue-green algae in the mounds demand that the build-ups formed in the photic zone, perhaps in water no more than several metres deep. This is indicated by beds of dolomitic wackestone or limy dolostone above some mound beds that suggest that the mounds may have formed in very shallow subtidal settings in the Port au Choix area. In the eastern part of the map area, the mounds are associated with large molluscs and with a facies-restricted trilobite fauna consisting of large individuals of *Illaenus* and *Bolbocephalus*. The presence of *Illaenus* may indicate a deeper, open-shelf setting for these eastern mounds (Fortey, 1975).

Orientation of linear mounds and ripple marks in carbonate sand lenses and beds suggest storm and/or tidal currents consistently swept north–south to northeast–southwest across the open platform. These trends are consistent with paleocurrent trends in the underlying Boat Harbour rocks. This may suggest that the orientation of the shelf trended northeast to east throughout the Early Ordovician.

Subtidal shelf deposition continued throughout the Catoche. However, cyclicity in the diagenetic dolostones at the top of the formation, suggests the shelf had begun to shallow before the Aguathuna Formation was deposited.

## *Aguathuna Formation*

*Definition and Distribution*

Yellow-weathering, microcrystalline dolostones and some shaly dolostones compose the Aguathuna Formation. The formation is thinly developed, recessively weathered and hence generally poorly exposed. It is exposed only on the eastern shore of Back Arm, on Square Rock offshore of the southern side of St. John Island, on the floor of a gravel quarry on the south side of Route 74 near Little Brook Pond, and on the north shore of River of Ponds Lake. This thin

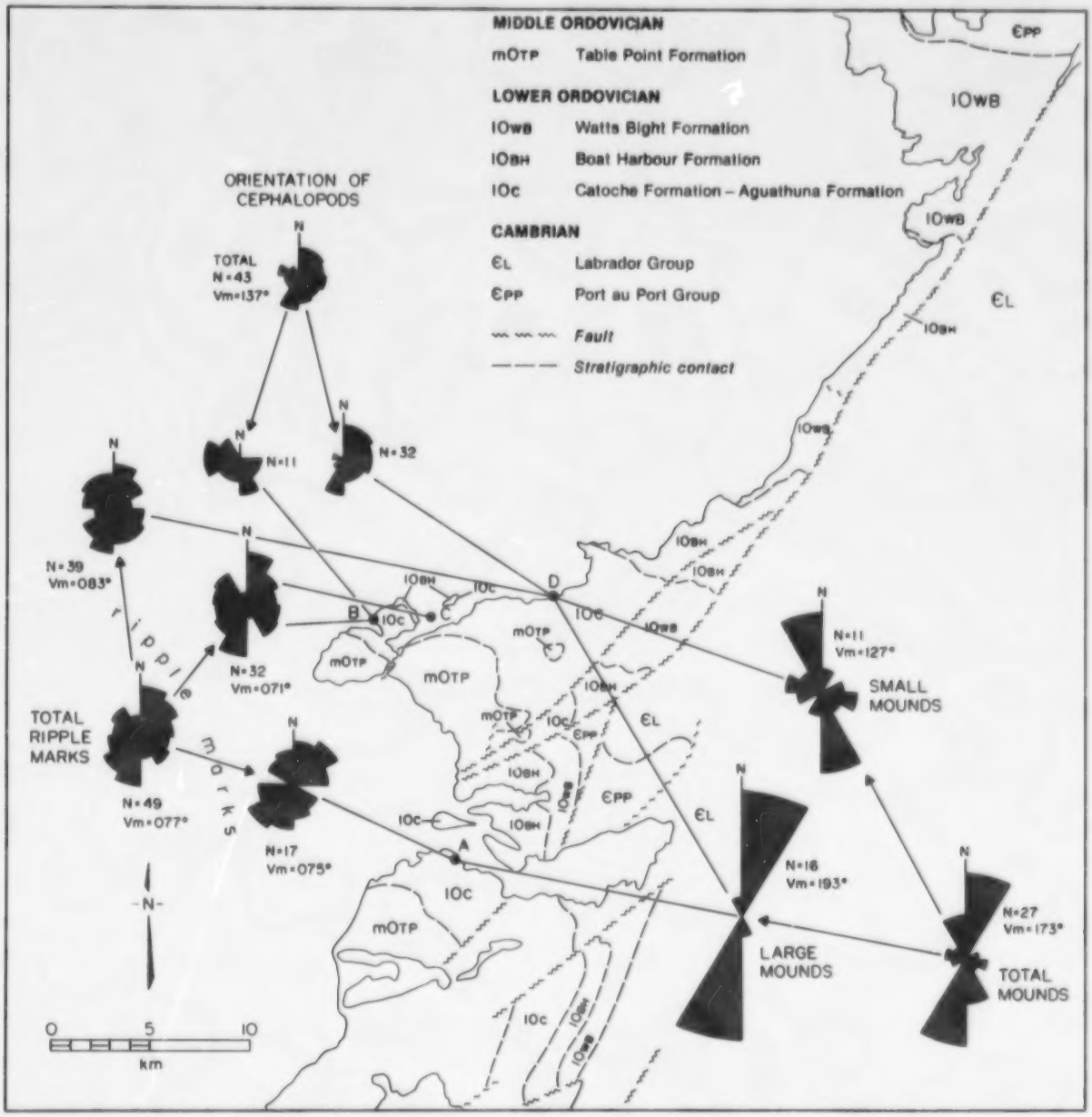



**Figure 10.** *Paleocurrents, Catoche Formation. A–Hawkes Harbour–Hawke Flat; B–Port au Choix Peninsula; C–Querrie Island; D–Bustard Cove.*

development of dolostone is assigned to the upper member of the formation (Knight *et al.*, 1991), which was locally deposited upon the St. George Unconformity in the Daniels Harbour to Port au Choix area.

The basal contact in the map area is a disconformity upon the Catoche dolostones. It is the local expression of the St. George Unconformity, which is a regional stratigraphic break in western Newfoundland (Knight *et al.*, 1991). The disconformity is best observed at River of Ponds Lake. The formation is conformably overlain by the lower cyclic member of the Table Point Formation (Table Head Group) at Back Arm and in the shore southwest of the western neck of Rivers of Ponds Lake. The contact lies beneath the first thick bed (60 cm) of dark-grey, nodular limestone of Table Head aspect. This bed at Back Arm rests upon a yellow, buff-weathering, fossiliferous, mottled dolomitic limestone and dolostone, the actual contact being a pronounced megastylolitic surface. The dolomitic limestone in turn rests upon microcrystalline dolomite. At Black Point, Pointe Riche Peninsula, 3 km to

**Table 3.** Faunal list of trilobites and conodonts recovered from the Catoche Formation in the Port au Choix–Bustard Cove area. Trilobites (Fortey, 1979); D. Boyce, personal communication, 1985; conodonts (Stouge, 1982)

TRILOBITES

*Strigigenalis brevicaudata* Boyce
*Grinnellaspis newfoundlandensis* Boyce
*Jeffersonia angustimarginata* Boyce
*Bolbocephalus convexus* (Billings)
*Peltabellia* sp. cf. *P. crassimarginata* (Cullison)
*Peltabellis* sp. cf. *P. willistoni* Lochman
*Petigurus nero* (Billings)
*Petigurus* sp. nov. A. Boyce
*Isoteloides peri* Fortey
*Benthamaspis hintzei* Boyce
*Ischyrotoma parallela* Boyce
*Uromystrum affine* (Poulsen)
*Strigigenalis caudata* (Billings)
*Punka* sp. nov. (= *Punka?* sp. indet., Fortey, 1979)
*Benthamaspis conica* Fortey
*Uromystrum* sp. cf. *U. affine* (Poulsen) of Fortey (1979)
*Catochia ornata* Fortey
*Bathyurellus abruptus* Billings
*Punka flabelliformis* Fortey
*Ischyrotoma anataphra* Fortey
*Jeffersonia timon* (Billings)
*Strotactinus insularis* (Billings)
*Carolinites genacinaca nevadensis* Hintze
*Isoteloides latimarginatus* Fortey
*Bolbocephalus kindlei* Boyce
*Benthamaspis gibberula* (Billings)
*Illaenus* sp. nov.
*Opipeuter* sp. cf. *O. angularis* (Young)
*Catochia glabra* Fortey
*Bathyurellus platypus* Fortey

CONODONTS

Fauna 5

*Scolopodus? gracilis* Ethington and Clark s.f.
*Acodus* sp. cf. *A. delicatus* Branson and Mehl
*Drepanodus? gracilis* Branson and Mehl s.f.
*Scolopodus quadraplicatus* Branson and Mehl s.f.
*Tropodus comptus* (Branson and Mehl)
*Oistodus inaequalis* Pander s.f.
*Scolopodus?* sp. C
*Drepanodus parallelus* Branson and Mehl s.f.
*Loxodus?* sp. aff. *L. bransoni* Furnish
*Protoprionodus* sp. A
*Oepikodus communis* (Ethington and Clark)
*Drepanoistodus* sp. B
*Drepanodus arcuatus* Pander
*?Microzarkadina marathonensis* (Bradshaw)
*Semiacontiodus* sp. cf. *S. asymmetricus* (Barnes and Poplawski)
*Oepikodus* sp. cf. *O. communis* (Ethington and Clark)
*Semiacontiodus asymmetricus* (Barnes and Poplawski)
*Bergstroemognathus extensus* Serpagli
*?Paroistodus parallelus* (Pander)
*Oistodus* sp. 1 Serpagli
*Scolopodus* sp. cf. *S. rex* Lindstrom
*Paltodus sweeti* Serpagli s.f.
*Juanognathus variabilis* Serpali

Fauna 4

*Drepanodus suberectus* Bransom and Mehl s.f.
*Scolopodus? gracilis* Ethington and Clark s.f.
*Drepanodus simplex* Branson and Mehl s.f.
*Acodus* sp. cf. *A. delicatus* Branson and Mehl
*Drepanodus? gracilis* Branson and Mehl
*'Scolopodus' quadraplicatus* Branson and Mehl s.f.
*Tropodus comptus* (Branson and Mehl)
*Oistodus inaequalis* Pander s.f.
*Scolopodus?* sp. C
*Drepanodus parallelus* Branson and Mehl s.f.
*Oneotodus costatus* Ethington and Brand
*Loxodus* sp. aff. *L. bransoni* Furnish
Gen. nov. A sp. nov. A
*Protoprionodus* sp. A
*Oepilodus communis* (Ethington and Clark)
*Drepanoistodus* sp. B
*Drepanodus toomeyi* Ethington and Clark s.f.
*'Scolopodus' emarginatus* Barnes and Tuke s.f.
*'Scolopodus' cornutiformis* Branson and Mehl s.f.

the west, dolomitized fossiliferous limestone beds of the middle part of the Table Point Formation appear to overlie a coarse rock breccia. Exposure there is poor however, and the actual relationship is obscure. Cumming (1968) described the contact as a disconformity. However, the dolomitization of the Table Point strata strongly suggests a dolomitization front here, and slickensiding on bedding planes (Levesque, 1977) suggests a fault may also occur (a view also shared by N.P. James, personal communication, 1984).

The disconformity is best observed (although incompletely exposed) at River of Ponds Lake. The basal contact is not so well exposed at Back Arm. It appears to directly place yellow-weathering, microcrystalline dolostones with apparent conformity upon dark diagenetic dolostones of the Catoche Formation. Drillholes spudded in Table Head limestones east of Port au Choix (Dickie and Lyn, 1979) pass down through the cyclic basal Table Head member and the Aguathuna dolostones conformably into the Catoche

diagenetic dolostones. Only in one drillhole (PC-79-1, Dickie and Lyn, 1979) does a 5-cm flat pebble conglomerate occur that suggests possibly some erosion or discontinuity at the contact.

*The Disconformity on River of Ponds Lake*

An irregular contact seperates dark-grey dolostones of the Catoche Formation from the Aguathuna Formation in the cove, on the northern shore of the western neck of River of Ponds Lake. The following description is compiled from both outcrop and numerous large, slightly dislodged blocks that lie along the shore near the outcrop. Breccias, silicified zones and waterlain chert-rich clastic sediments are associated with the contact. The Catoche dolostones consist of typical burrow-mottled, dark-grey dolostones, which are extensively silicified and cut by numerous fractures. Black chert that frequently displays burrow mottling, white-banded chalcedony and crystalline megaquartz occur in the dolostones. A poorly sorted breccia of mottled dolostone, black chert and some white quartz fragments floating in a matrix of dark-grey crystalline dolomite occurs at the top of the Catoche Formation. Yellow- to buff-weathering, very fine dolostone, infills between upstanding clasts at the top of the breccia (Plate 54) and penetrates deeper into the breccia along a thin network of veins. Cavities below the surface are filled by breccia, yellow-weathering dolostone and chert granules (Plate 55).

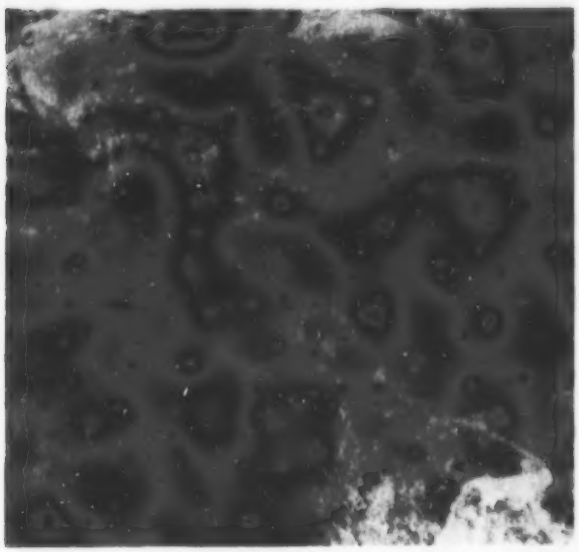


**Plate 54.** *A breccia of black chert and dark-grey dolostone having a yellow, fine dolostone (light coloured areas between clasts) matrix. The breccia occurs at the top of the Catoche Formation at the west end of River of Ponds Lake.*

Brownish, 300 μm hypidotopic dolomite surrounding clasts of 170 μm hypidotopic brown dolomite forms the brecciated dark-grey dolostones. Fine, 34 μm pyrite and amorphous iron oxides are disseminated through the dolomite. The black chert appears to replace the dolomite. A narrow

**Plate 55.** *A displaced block of dolostone containing the Catoche–Aguathuna contact (dashed line) at the west end of the River of Ponds Lake. Catoche dolostone (CF) is overlain by Aguathuna dolostone (AF), which shows some stratification, and pockets of pebbly sandstone (arrows) composed of chert grains.*

zone of mixed dolomite and chert occurs behind a dark line of insoluble residue that marks the silicification front. The chert, which in plane light reveals a mottled, clear to brown structure surrounding variably shaped pores, consists of cryptocrystalline and mega quartz. The cryptocrystalline quartz is very dusty with zones of slightly coarser, up to 80 μm, microquartz. Voids within the chert are filled by dusty to clear, hypidomorphic megaquartz or both fibrous microquartz and clear megaquartz. Remaining space is filled by coarse dolomite that encloses euhedral quartz crystals. Microlites of possible sericite or anhydrite occur in the coarser megaquartz.

The contact is irregular due to a number of angular depressions with a depth and width of 40 cm (Plate 55). Yellow-weathering, poorly stratified dolostones of the Aguathuna Formation fill the lows. Thin bedding and lamination occur in dolostones that overlie both the depression fills and the highs that occur at the contact. Also present, however, are a number of lenses of granular to pebbly sandstone (Plate 55) that occupy the floor of depressions and onlap the margins of highs. Slabbed samples of the clastic rock reveal an intercalation of pebbly sands with 3 to 10 mm layers of buff-weathering, dolomite mudstone. The layering is gently inclined with small flat pebbles imbricated slightly more steeply in the same direction. The rounded to angular granules with maximum size of 9 mm consist of several varieties of chert. They include:

1) Dusty to clear quartz having oriented inclusions of sericite or anhydrite(?); 2) equant megaquartz; 3) cryptocrystalline chert; 4) combined mega- and

microquartz having numerous spherules of radiating fibrous quartz growing in the coarse groundmass; 5) radiating and interlocking, lath-shaped, length-slow megaquartz composed of 0.15- to 0.68-mm-wide by 1.8-mm-long crystals, which have numerous inclusions that are oriented after an earlier fine fibrous fabric. The ghosts of a felted mat of crystals, 0.017 mm by 0.204 mm in size, are preserved in one such grain—the lath-like quartz crystals pseudomorph the original crystal fabric; 6) clear equant megaquartz similar to chert from the dolomite breccias; and 7) a silicified ooid of brown concentric layers of microquartz fringed by a megaquartz cement.

Also present in the pebble bed are phosphatic shell remains and intraclasts of dolostone. The dolostone pebbles consist of brownish dusty hypidotopic dolomite, 25 μm crystal size. The intraclasts are set in a fine matrix of 20 to 50 μm hypidotopic dolomite that also forms the intercalated dolostone laminae between granular layers. Blocks of chert–pebble conglomerate (Plate 56) coincide with poorly exposed Aguathuna strata at the northeastern shore of River of Ponds Lake (NTS 12I/11, grid reference 4784 55942).

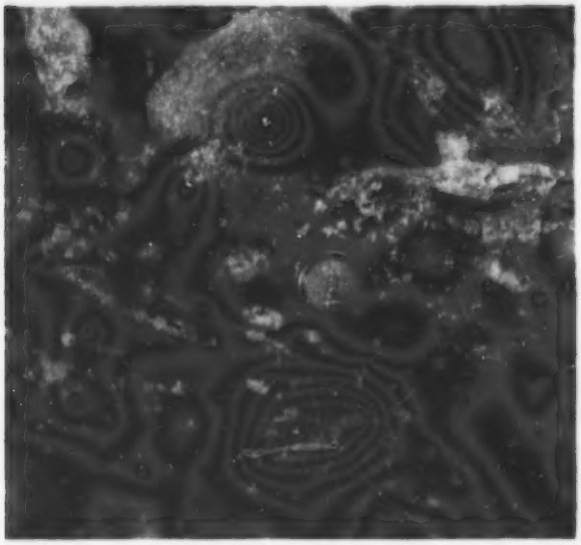


**Plate 56.** *A pebble conglomerate of chert set in a siliceous dolostone matrix. The rock type occurs in one of a number of displaced blocks at the northeast end of River of Ponds Lake.*

*Thickness*

At Back Arm, the formation is 5.07 m thick. A thickness of 3 to 4 m occurs in a covered interval between underlying Catoche diagenetic dolomites and overlying basal Table Head limestones on Horn Island, southeast of St. John Island in the tickle known as Good Bay; less than 3 m is likely in a covered interval 1.8 km east of Black Point, Pointe Riche Peninsula. The formation thickness ranges between 4.1 and 7.0 m in the drillholes east and southeast of Port au Choix (Dickie and Lyn, 1979). A covered interval within the cove at the western neck of Rivers of Ponds Lake conceals a maximum of 15 m of Aquathuna Formation between Catoche dolostones and Table Head limestones.

Outside the map area, the formation is thicker than 60 m. This significantly thicker section is dominated by a lower member, which is not found in the map area. The rapid thickness increase occurs as the formation is traced southeast across the Torrent River fault in the vicinity of River of Ponds Lake. As noted by Knight and Boyce (1984), the 5 m section exposed at Back Arm contains dolostones that compare to those found in the top 6 to 15 m of the formation in the sections, near Table Point. A major part of the Aguathuna Formation was therefore either not deposited in the map area or it was eroded following uplift. The latter is probable because the area formed part of a major structural high on the platform controlled by northeast-trending faults that were active near the end of Arenigian time.

*Lithology*

The Aguathuna Formation in the map area consists mostly of yellow-weathering, pale-grey, to grey microcrystalline dolostones. Green-grey shaly dolostone is interbedded with the dolostone on Square Rock and nodular, fossiliferous, argillaceous, green-grey dolomitic limestone beds occur at the top of the formation at Back Arm. Nodular chert layers occur in dolostones on the northeast shore of River of Ponds.

The dolostones occur in beds 20 to 80 cm thick (Plate 57). Bedding planes are both planar and sculptured by smooth pits and protuberances a few centimetres in scale (egg-carton structure, stylolites). Internally, many of the dolostones appear structureless, but some beds reveal a vague colour mottling in the lower part of beds with planar-thin bedding and lamination in the top 20 cm of beds. Polygonal mudcracks, some with well-developed raised edges and microripples in the cups, occur in shaly dolostones on Square Rock and on some overturned loose blocks at Back Arm. However, in thin section, wedge-shaped to indistinct, micro-fractures turning up poorly preserved microlaminations occur in the apparently structureless dolostones. Dolostones on Square Rock also contain small quartz-lined vugs.

The dolostones consist of 10 to 50 μm, xenotopic to hypidiotopic dolomite with denser, <10 μm dolomite forming microlaminations 0.3 mm in thickness in the coarser microspar. Quartz silt, 50 to 70 μm in size, is scattered through the coarser dolomite. Scattered large dolomite crystals, 0.5 mm in size, sit in the microdolomite. Megaquartz occurs in small nodules 0.35 to 1.0 mm in size. They are rich in inclusions, and dusty vacuoles in plane light appear to outline a feathery-fibrous crystalline texture. Pyrite framboids are common.

Within the top metre of the formation at Back Arm, are two beds 40 to 50 cm thick composed of dolomitic, argillaceous lime packstone and calcic dolostone. The basal bed of dolostone has lime burrow mottles and the upper bed,

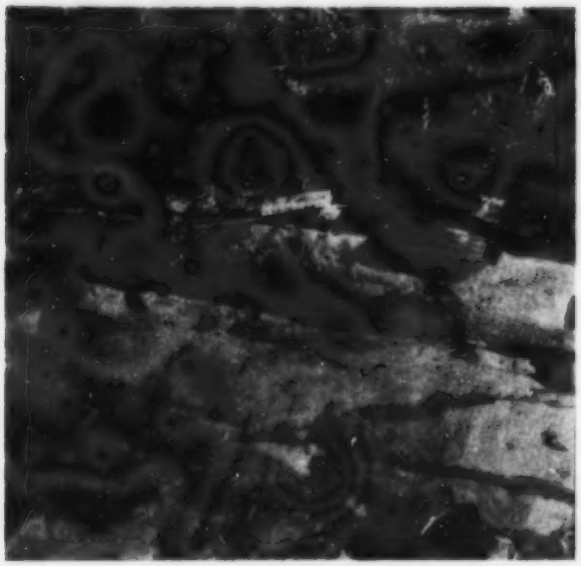


**Plate 57.** *Buff-weathering dolostone of the Aguathuna Formation, Back Arm, Port au Choix.*

which has dolomite burrow mottles and lime nodules, also contains abundant ostracodes, rare crinoid platelets and brachiopod shells displaying fibrous microstructure. The trilobite *Bathyurus perplexus* Billings is also present in the bed. Structural detail is well preserved in the ostracode shells where a 10 μm finely granular outer layer overlies a 60 to 150 μm, perpendicular prismatic layer. Some shells are extensively micritized and are enclosed in a 0.27 mm zone of dolomitic micrite with clear microspar-filled tubules and pyrite speckling the edge of the micritic zone. Most ostracode carapaces are filled by dark dolomitic micrite. Carapaces that were not infilled are commonly recrystallized and small clusters of micrite and microspar blade cements are attached to the shell. Remaining open space is filled by 150 μm blocky spar.

*Fracture-Fill Deposits of the Aguathuna Formation Cutting the Catoche Formation*

Also described here as part of the Aguathuna Formation are structurally controlled sediment fills that cut limestones of the middle of the Catoche Formation on the shore at Hawke Point and Hawke Flats at the mouth of Hawkes Bay (Plate 58) and a mound bed (Unit 15a, Appendix 1, Section 9, Figure 9) in the section at Port au Choix. The discordant sediment fills consist of fault-controlled dolomitic chert sandstones at Hawke Point and joint-controlled dolomitic mudstones at Hawke Flats. The fractures at Port an Choix are irregular, filled by dolomitic mudstone but are oriented suggesting they still have a structural control. Both sediments are anomalous to the Catoche Formation but compare very closely to rock types known to occur in the Aguathuna Formation at Table Point and on the shores of River of Ponds Lake.

On the north side of Hawke Point, dolomite-cemented sandstones composed of chert and dolomite sand grains occur for several metres along a northeast-trending normal fault (Plate 58a). The fault, which trends 040°, is nearly vertical, braids locally and displaces almost flat-lying Catoche limestones a few tens of centimetres. The fault can be traced over a kilometre southward into Trappers Cove where no sandstones are associated.

The yellow-weathering chert sandstones filled open spaces, 30 cm wide, along the fault. Sedimentary structures in the sandstones include curved to inclined planar stratification, some dipping up to 40° in a northwest direction, and local discontinuity surfaces (Plate 58b). Two fractures trending 205° and dipping 70° to the west, crosscut and locally displace the stratification. The wall rock is dolomitized to pale grey, fine dolostone for up to 30 cm away from the fault plane.

The sandstones are mostly poorly sorted, matrix-supported, very coarse to coarse grained and have some dolostone intraclasts. However, locally well-sorted, fine sandstones occur. The sand grains consist of chert, chalcedonic quartz, oolitic chert and clear quartz having dusty inclusions. In some grains, the inclusions are so distributed that they appear to mimic an earlier fabric and earlier grain boundaries. Some rare silicified skeletal fragments and calcareous bioclasts and lithoclasts also occur. These include ooids, echinoid remains, unidentifiable shell fragments and chitinous grains. Framboidal and aggregated crystals of pyrite, authigenic euhedral quartz enclosing sericite (or anhydrite) and small micas and rarely a nucleus of a quartz grain, and a rare zircon grain also occur in the sandstones. Hypidotopic to xenotopic, equigranular to porphyrotopic dolomite crystals up to 0.2 to 0.3 mm in size cement or act as a matrix in the sandstones. The dolomite is generally cloudy and some dolomite crystals also have dusty centres or central zones.

At Hawke Flat, 2-cm-wide dykes of dolomitic mudstone cut gently dipping Catoche limestones (Plate 58c). The dykes strike 035° and dip 62° southeast. The dykes are parallel to joints that have remained closed; however, the dykes do sidestep from joint to joint by slight changes of orientation.

Slabbed surfaces of the mudstone fill reveal a series of almost flat-lying sediment layers that are slightly curved upward against the joint footwall and merge into a 3-mm-thick homogeneous to deformed zone adjacent to the joint's hanging wall. Discontinuity surfaces occur at one point and the overlying layering is convoluted. In thin section, the fine-grained fill consists of 20 to 50 μm rhombic dolomite crystals many with broken points. Slightly finer crystals, together with dark intercrystal amorphous matrix, constitute the tops of the bedded geopetal fill. Rare quartz and mica silt occur together with a few, 2-mm bioclastic, dolomite mudstone fragments probably derived from the wall rock.

At Port au Choix, irregular, branching 0.5- to 3-cm-wide fractures filled by green-buff-coloured dolomitic mudstone cut the boundstone of subunit 15a of the Catoche Formation. The fractures trend 040 to 053° essentially parallel to joints in the same area. The joints have narrow zones of

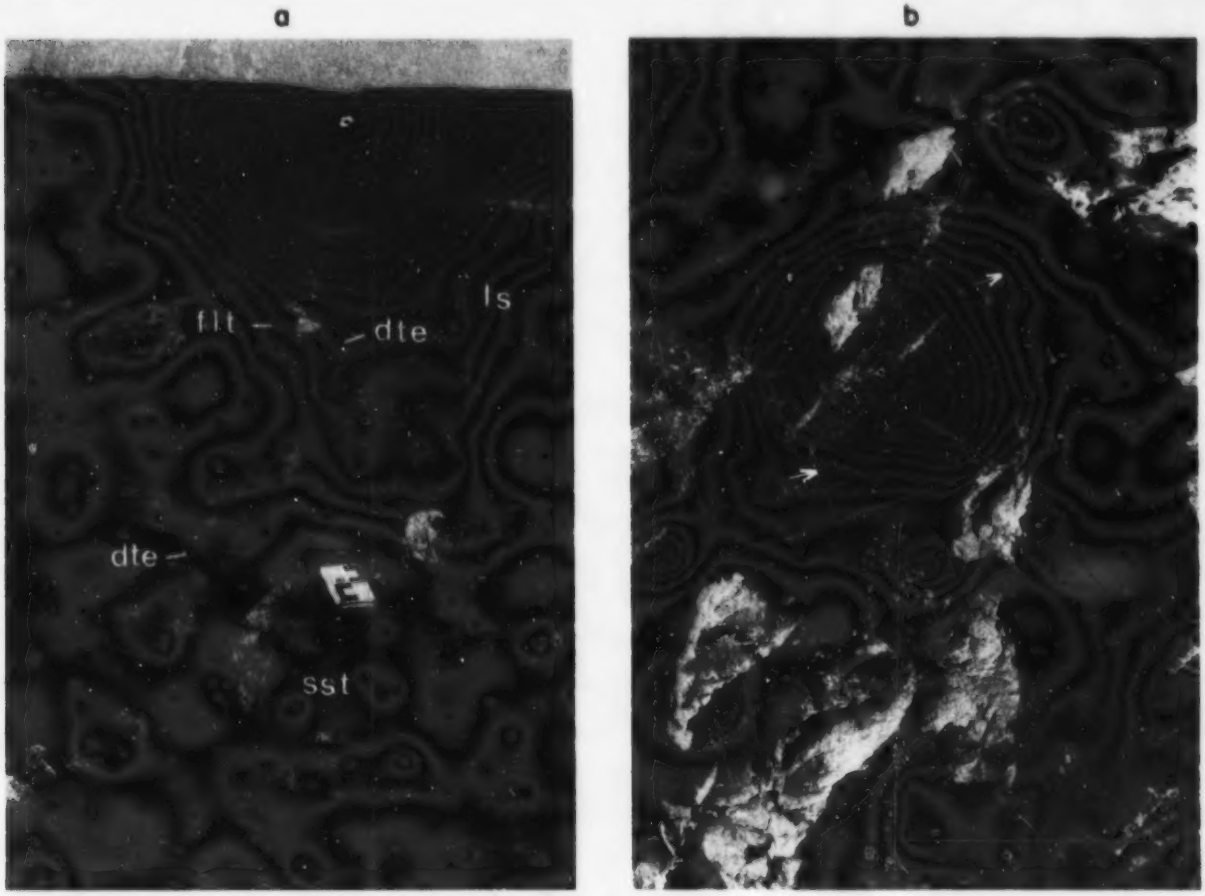



**Plate 58.** *(a) Northeast-trending fault (flt) cutting limestone (ls) of the Catoche Formation at Hawke Point, Hawkes Harbour. Preserved along the fault are pockets of cemented quartz sandstone (sst); dolostone (dte) replaces the limestone in a narrow zone close to the fault plane; (b) the sandstone displays depositional layering, which is crosscut obliquely by two fractures that displace layering (arrows); (c) three kilometres to the east at Hawke Flat, Hawkes Harbour, dolomite mudstone fills easterly dipping joints that also cut rubbly weathering, well-bedded limestone of the Catoche Formation.*

dolomitization adjacent to them comparable to the dolomitization adjacent to the fault fills at Hawke Point.

*Deformation and Brittle Fracturing; Square Rock, St. John Bay*

Bedding on Square Rock is disrupted locally in an irregular fashion by breccias and also by a network of brittle fractures. The breccias and fractures are filled by dark-grey, vitreous cryptocrystalline dolomite, and a later white sparry dolomite cement (Plate 59). The early dark dolomite fills spaces between rotated dolostone blocks in the breccias. It also fills hairline to centimetre-wide fractures that branch in an irregular, curved to angular blocky fashion and taper downward, cutting through one or more beds. The dark dolomite is probably geopetal dolomite. It consists of 0.12- to 1.2-mm anhedral to euhedral dolomite rhombs that form mostly an unsorted, disordered agglomeration in the fractures. Brown dusty, amorphous iron oxides thread around rhombs and form a concentrated line at fracture margins. Petrographic examination of the fracture walls indicates that clear rhombic- to erosion-blunted crystals of the host rock project out into the fracture with the amorphous iron oxides filling between crystals. Locally radiating elongate (core) to equant (rim) megaquartz having a semicircular shape, projects into the fracture from its walls. Where open space remains at the top of the fractures or in the breccias, it is filled by the later white dolomite spar.

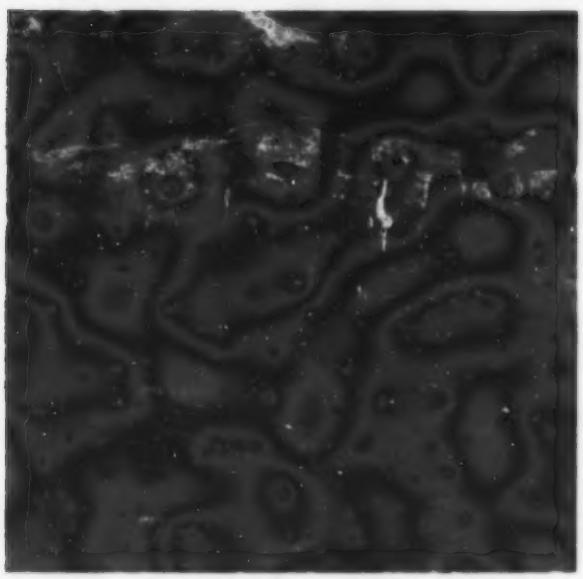


**Plate 59.** *Bedded dolostone of the Aguathuna Formation, Square Rock, St. John Bay. The dolostone is cut by an extensive network of brittle fractures (arrow), which are filled by dark vitreous dolomite (A) and by white sparry dolomite cement (B).*

The well-bedded dolostones on Square Rock can be traced into breccias composed of small to large (20 cm) dolostone blocks. The breccias reaching 0.5 to 2.0 m in thickness occupy areas a few metres square. In one instance, the breccias are developed over a system of gentle arches developed in bedded dolostone. The arches have a height of 20 to 100 cm and width of a few metres. One set of arches trend 150 and 190° and are intersected by a third arch trending 265°. Locally, margins of the arches are delineated by fractures that trend parallel to the arch and that offset bedding for a few centimeters. Preliminary observation of the island suggests that the pods of breccia developed in different beds and that the dark geopetal filled fractures terminate at the tops of different beds. Prominent white, sparry, dolomite-filled, slightly irregular joints trending 244° dipping 72° northwest, and 105° dipping 58° south, cut the dolostones of the island. They crosscut the dark geopetal-filled fractures and are probably related to late tectonic movements.

*Paleontology and Age*

The microcrystalline dolostones of the Back Arm section are mostly unfossiliferous. However, the topmost bed of nodular, bioclastic, argillaceous dolomitic limestone has yielded the ostracod *Eoleperditia bivia* (White) and the trilobite *Bathyurus perplexus* Billings (Boyce, 1983). The fossils suggest an early Middle Ordovician age. Conodonts from the section are of early Whiterock age and part of the same faunal assemblage contained in the basal rocks of overlying Table Point Formation (K. Stait, personal communication, 1988).

*Depositional Environment*

The thinly developed Aguathuna Formation in the map area was deposited unconformably upon an eroded karst surface developed upon Catoche dolostones. The microcrystalline dolostones display structures that together suggest the formation was deposited in a restricted tidal-flat setting. The few beds composed of mottled bases and planar-laminated tops reflect shallowing-upward sediment accretion having burrowed lagoonal, pond or lower intertidal muds capped by high intertidal and supratidal, frequently mudcracked, cryptalgal laminites. Small siliceous concretions in the dolostones probably formed by replacement of minor displacive nodular sulphate that grew in the tidal-flat muds.

The microcrystalline dolostone and the uncommon evaporite relicts suggest diagenesis of carbonate muds by hypersaline brines. Paucity of evaporites suggests the environment was not strictly comparable to that of the Trucial Coast where nodular and layered nodular sulphates are an important signature of dolomite muds of the Persian Gulf sabhkas (Kinsman, 1976). The Bahamian tidal flats, on the other hand, contain rare evaporites and subordinate protodolomite (Shinn, 1983) and may not form a good analog for the Aguathuna dolostones.

Several lines of evidence suggest that the dolostone facies was deposited under locally restricted conditions controlled by subdued topography upon the St. George Unconformity. The dolostones are geographically restricted to the Daniel's Harbour–Port au Choix area in western Newfoundland. Early

Whiterock conodonts in the dolostone compare to those in the overlying basal peritidal carbonates of the Table Point Formation (see below). This indicates that the facies, although geographically restricted, is contemporaneous with other facies during the Whiterock transgression. The peritidal carbonates of the Table Point Formation, however, show abundant evidence of humid unrestricted tidal-flat deposition (see below). If this is so, it suggests that some factor restricted water circulation and allowed the local development of hypersaline conditions. A faulted platform is suggested by the structurally controlled sediment-filled caves at depth below the unconformity and by the fault-controlled thickness changes in the formation across the Torrent River fault (Knight, 1985; Knight and Boyce, 1984; Knight *et al.*, 1991). This suggests that the dolostones represent a carbonate-mud facies laid down in areas of restricted circulation on an eroded, block-faulted platform during the early stages of marine flooding of the St. George Unconformity.

The physical expression of the St. George Unconformity in the area is rather muted. However, biostratigraphic and lithostratigraphic considerations show that uplift and substantial erosion occurred. Stratigraphic relationships (upper Aguathuna Formation above Catoche dolostones) indicate that karst erosion of at least 40 to 50 m of dolostones (lower Aguathuna Formation) occurred northwest of the Torrent River fault. The northwestward-thinning veneer of upper Aguathuna Formation upon the unconformity from Daniels Harbour to the map area suggests, however, that erosion had subdued the structurally controlled karst landscape to an uneven plain before the younger sediments were laid down.

Diagenetic dolostones of the Catoche Formation at Port au Choix show no apparent effect of the uplift nor little evidence of paleokarst. However, a paleokarst surface having local relief, a paleosoil, and overlying waterlain gravels are locally developed on the unconformity. Open spaces that developed subterraneously along faults and joints, cutting the underlying Catoche Formation, were filled by dolomite–chert sands and muds at this time.

Most significant is the development of breccia in Catoche dolostone and pebbles of the dolostone lying on the disconformity. Their presence shows that some stages of the dolomitization of Catoche limestone occurred soon after deposition and before karstification. The dolomite breccia, which is coloured by amorphous iron oxides and contains chert nodules, is interpreted as a paleosoil. Widespread chert in the paleosoil suggests that the soil may have been a silcrete, because chert locally replaces the dolomitic matrix of the breccia. It is now widely accepted that chert commonly replaces evaporitic sulphates and may provide the only evidence of evaporites in a carbonate succession (Folk and Pittman, 1971; Chowns and Elkins, 1974; Milliken, 1979). Relict evaporitic textures in chert pebbles within gravel pockets of the paleokarst clearly point to some evaporites either within eroded Catoche or Aguathuna carbonates or forming at the disconformity. Replacement of the evaporites by silica, which was then subsequently reworked as insoluble detritus at the karst surface into overlying gravels, suggests that this replacement process is both rapid and essentially syndepositional. It is interesting to speculate that silicification of this kind is essentially associated with subaerial exposure of platformal carbonates when the precipitation of evaporites and subsequent silica replacement occurs at suitable sites upon the surface.

The presence within the formation of fractured and locally brecciated dolostones associated with arched bedding planes on Square Rock, St. John Bay, suggests that syn- and/or early post-depositional deformation affected the dolostones at least in this area. Dark, finely crystalline geopetal dolomite and later, white dolomite spar cement, healed fractures and formed matrixes of breccia. No comparable structures occur in the section at Back Arm, 12 km to the southeast. This suggests that faults were possibly active in the area during and after deposition of the dolostones. This hypothesis is attractive since the dolomites of Square Rock lie close to a major northeast-trending fault to the east along Good Bay. This fault may strike into Back Arm and Gargamelle Cove hence placing both Black Point and Square Rock on the same structural block.

## Table Head Group

### *Introduction*

Limestones of Middle Ordovician age complete the stratigraphy in the map area. In western Newfoundland, the group contains four formations (Klappa *et al.*, 1980) of which only the basal Table Point Formation is preserved in the map area.

In the map area, the formation appears to rest conformably upon the underlying St. George Group. The base of the group is, however, extensively affected by dolomitization that transgresses upward through basal strata for many metres. The dolomitization front at Black Point, Pointe Riche is roughly parallel to bedding. Just a few hundred metres south of Black Point however, the front injects upward several metres into the rubbly weathering, well-bedded, Table Point limestones. Here, they are replaced by porous crystalline dolomites cemented by sparry dolomite, the rock resembling pseudobreccia. Conodonts recovered from the limestones at Black Point (Stouge, 1980) suggest they indeed lie at least 40 m above the base of the formation when compared to the type section at Table Point, 40 km to the south. N.P. James (personal communication, 1984) agrees with Stouge (1980) and believes the strata lies nearly midway through the formation. This suggests that the contact does not actually occur on the north side of Black Point but rather is to be found in the long covered interval toward Blanche Point. Woodard (1957) described an unconformity on the north side of St. John Island but there is extensive secondary dolomitization of the Table Head limestones in this area and his interpretation cannot be confirmed.

At Back Arm, where the basal contact is exposed, it is conformable. A solution pitted upper surface to the highest

bed of the Aguathuna Formation is probably a stylolite rather than the product of subaerial exposure. The early Middle Ordovician trilobite *Bathyurus perplexus* Billings in the same bed and Whiterock conodonts in the Aguathuna (K. Stait, personal communication, 1988) suggest that there is no appreciable time gap represented by the surface.

### *Table Point Formation*

#### *Definition and Distribution*

Rubbly weathering, well-bedded, fossiliferous, dark-grey limestone, pale-grey fenestral limestone and minor dolomitic limestone and dolostone comprise the Table Point Formation. The formation is well exposed on the Pointe Riche Peninsula, the shoreline of Ingornachoix Bay, the shoreline south of River of Ponds and on St. John Island, Flat Island and Twin Islands. Inland, it is generally poorly exposed even though it forms ridges that locally rise to 60 m above adjoining valleys. Scattered exposures occur on the shores of River of Ponds Lake. The base of the formation has already been discussed above in the Aguathuna Formation and in the introduction. No upper boundary is exposed in the area.

#### *Thickness*

The full thickness of the Table Point Formation at its type section is 247 m (Klappa *et al.*, 1980). At most, only the basal 100 m of the formation likely occurs in the mainland part of the map area. Stouge (1980) measured approximately 50 m of section at Gargamelle Cove, the section lying at the base of the formation. The section at Black Point, Pointe Riche Peninsula, which is known to lie stratigraphically some 40 m above the base, contains approximately another 40 m of section (Knight, 1977). At least 120 m of section is present on Flat Island.

#### *Lithology*

Klappa *et al.* (1980) described the formation as a succession of 'mostly bioturbated, bioclastic wackestones and packstones with intercalated lime mudstones and peloidal grainstones'. They also listed green-grey dolomitic limestone and dolostone beds as a conspicuous but minor component of the lower part of the section. Klappa and James (1980) described a series of small sponge-dominated bioherms associated with bioclastic grainstones within the formation from various locations in western Newfoundland including Pointe Riche and St. John Island.

Within the map area, the incompletely exposed formation consists of three major facies associations. The first, called the cyclic lithofacies association, forms a basal member, 3 to 16 m thick. It is best exposed near Port au Choix, but is apparently absent on Horn Island 4 km to the northwest in St. John Bay. It consists essentially of interbedded lime mudstone, wackestone and dolomitic lime mudstone and dolostone, with some other minor facies. The second, called the fenestral limestone lithofacies association, is a succession of pale-grey, bioclastic, peloidal wackestones and mudstones that are rich in fenestra, some of which have the properties of stromatactis. This facies occurs only in the area immediately around River of Ponds. It is also not clear if it is laterally equivalent of the basal cyclic member or partly overlies it. Recent mapping in the Bellburns map area to the south (Knight, 1985) shows it to overlie the basal cyclic member. Scattered outcrops on the northwest shore of River of Ponds Lake suggest that this relationship holds true in the map area. The thickness of the facies is not known. The third major facies association consists essentially of the rock types described by Klappa *et al.* (1980) and Klappa and James (1980) and will be referred to here as the bioclastic wackestone–packstone lithofacies association.

*a) Cyclic Lithofacies Association.* This lithofacies association consists of alternating beds of massive- to nodular-bedded, grey limestone and buff-weathering, massive, grey, fine dolostone or laminated and fenestral, dolomitic lime mudstone or dolostone. The two rock types are also arranged in vertical order within single beds; couplets range in thickness from 1 to 3 m. Bases to some of the higher beds are irregular suggesting scouring. Some scalloped depressions were also noted at tops of beds with overlying laminations thickening and thinning into the hollows. The nodular limestone dominates for the first 4 m of the member where it is rich in shaley stylolites.

The massive limestone consists of lime mudstone composed of dark, blotchy micrite with a plentiful network of spar filled fenestra. The fenestra range from small, irregular, isolated to interconnected 0.2 to 0.5 mm voids, to larger nonlinear voids 0.15 mm wide by 2 to 6 mm in length. Larger, irregular lensoid fenestra 1 mm x 6 mm in size also occur. Clear equant microspar and spar, with 20 to 350 μm, crystals (size depending on increasing size of void) fill the fenestra. The finest fenestra locally occur in distinct layers alternating with micritic layers. Disarticulated ostracod shells and rare brachiopod and trilobite fragments are scattered sparsely through the micrite.

The top of each cycle consists either of a laminar fenestral fabric, or of planar lamination to very thin planar stratification composed of lime mudstone. Several beds grade up into generally structureless dolostone. Locally, the lamination is disrupted and upturned, suggesting mudcracks.

Dolostones at the top of the cycles are composed of 10 μm microspar with little evidence of porosity. However, the laminated limestones vary from bed to bed. In some beds, the lamination consists of 1 to 4 mm laminae. They consist of micrite laminae having a fine, poorly preserved peloidal fabric and numerous small 100 μm irregular to vertically oriented, interparticle fenestra that give a spongy texture, alternating with 0.3 to 0.6 mm laminae of dense, generally fenestra-free micrite. Some articulated ostracode shells lie concordantly within the layering. Some larger fenestra also occur that can partly engulf the ostracodes but whose formation was not controlled by the shells. Edges of shells are partly micritized up to 20 μm into the shell. Although

the main fabric of the fenestral laminae is indistinct 20 μm micrite peloids, one lamina displays a number of bushes 1.8 mm in size of vertically radiating filaments. They are similiar to the filamentous tussocks of Bertrand-Sarfati (1976) and *Garwoodia* (Wray, 1977, Figure 23). The spar-filled filaments are 20 μm wide by 60 μm long.

However, the tops of other beds display a laminar structure in which the fabric is produced by abundant primary laminar to interparticle fenestra set in a dark peloid mudstone–wackstone. Bioclasts of rare sponge, in complete and broken ostracodes, and calcispheres occur. The ostracode's shell structure is commonly poorly preserved with ends of shells micritized. *Renalcis* and *Girvanella* also occur. *Girvanella* is associated with micritized particles.

The laminar to irregular interconnected fenestra are cemented by both fibrous and equant cements. The interparticle and smaller fenestra are generally cemented by 10 μm blocky microspar. Dusty, radiaxial fibrous calcite cements occur in the large, stromatactis-like voids. The cavities include both flat to irregular floors and, generally, an irregular pendant-like roof having peloid bushes projecting downward from the overlying peloidal framework. The fenestra lie both parallel and oblique to bedding. Only in some instances, where the fibrous cement is overlain by fine internal sediment that filled the open space beneath spar cemented peloid pendants, does the fibrous cement appear to have grown from the floor. Other cavities were closed by the meeting of floor and roof cements.

An early micrite cement also occurs in some fenestra. It forms a fine deposit 500 μm wide along the floor and roof of pores, locally bridging the space at narrow necks. Pendant cements of short-bladed spar occur on the upper shell of whole ostracodes; remaining intraparticle space is filled by blocky spar.

Fine fractures, healed by clear equant spar, offset the peloid and interparticle cements, and fossil fragments. One such fracture could be traced across a 'stromatactoid' cavity as a faint ghost in the radiating cement. On the other hand, the same fracture does not cut, even as a ghost, late blocky calcite spar in a second pore even though the fracture occurs on each side of the pore. The fibrous cement in the 'stromatactoid' voids is affected by sutured stylolites.

*b) Fenestral Limestone Lithofacies Association.* This lithofacies consists of 1 to 2 m beds of pale-grey to white-weathering, pale-grey fine-grained limestone that is rich in fenestra (Plate 60). Beds consist of layers 10 to 20 cm thick of bioturbated, fossiliferous peloidal wackestone, and fenestra-rich lime mudstone–wackestone. The fenestra-rich layers dominate the top half of beds. They consist of layers of irregular and tubular fenestra and 'stromatactoid' voids and layers of dominantly laminar fenestra, the latter usually capping beds. Lamination is present in some laminar fenestral layers.

The bioturbated peloidal wackestones enclose large high-spired gastropods and straight cephalopods. Shells of both molluscs were neomorphosed and are now preserved as calcite- or dolomite-cemented molds. Burrows are commonly replaced by buff-weathering, fine dolomite.

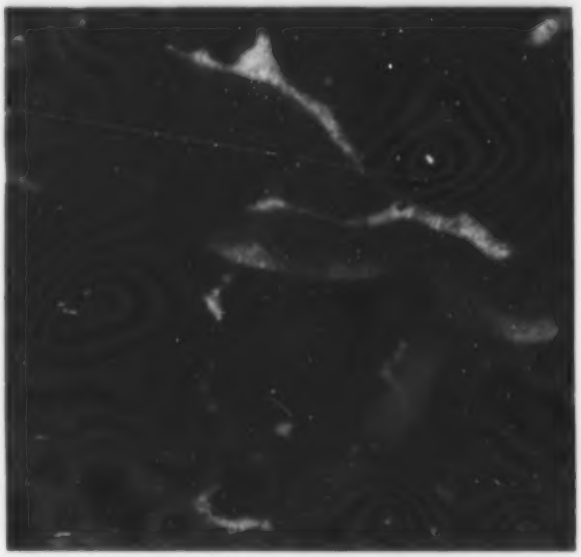


**Plate 60.** *Fenestral and 'stromatactoid' lime mudstones of the basal Table Point Formation. Fenestra are occluded by calcite spar. 'Stromatactoid' cavities contain geopetal carbonate mud and fibrous and blocky cements.*

The fenestra-rich limestones consist of a dark, blotchy, micrite groundmass that locally preserves a clotted texture of indistinct, 50 μm peloids. Whole and disarticulated ostracodes are scattered through the mudstone. Although the living chambers of the whole ostracode are mostly cemented by clear equant, 20 μm spar, some also contain light-colored geopetal micrite. Radial spherulites, 50 to 100 μm in size, also occur locally in the micrite.

Fenestra in the limestones vary from fine, 50 μm wide by 400 μm long tubules, to millimetre-scale irregular to laminar fenestra, to centimetre-scale 'stromatactoid' voids. Density of fenestral porosity varies considerably from layer to layer; 'stromatactoid' layers contain few fine tubular or larger irregular fenestra and have a low density (1 per 10 sq. cm) of 'stromatactoid' voids. However, both fine tubular fenestra and the millimetre-scale irregular fenestra are very common in interleaving layers where 'stromatactoid' voids are absent.

The fine tubular fenestra are always filled by clear, equant, 10 μm spar. The larger fenestra, which have irregular pendulous to protuberant floors, contain several different types of cement. Most common are 300 μm, radiaxial fibrous mosaic (Bathurst, 1975), and blocky, 200 to 300 μm, equant cements. Other fenestra have a fringe cement of 100 μm dogtooth spar or blunt, bladed voids. The remaining space is then closed by blocky spar. Geopetal sediment is rare in these fenestra, which can cut across ostracode shells embedded in the host micrite.

The 'stromatactoid' voids not only differ in size from the smaller irregular fenestra but also by virtue of their sharp, smooth, flattish to curving floors that contrast with their irregular pendant roofs. The 'stromatactoid' voids include geopetal sediment, layered fibrous roof cements and late coarse blocky cement. The geopetal sediment is mostly recrystallized to brownish, 50 to 150 μm, xenotopic spar. Layering shown by brown banding occurs in the fibrous cements and in some instances the cement is overlain by an outer layer of clear, equant spar in optical continuity with the rays of the fibrous cement bundles. Locally, the fibrous cement passes into spherulitic growths and obscure matted fabrics. Whole ostracodes, where they form part of the roof, are filled by radial fibrous cement.

Lying closely beneath the 'stromatactoid' voids, and mimicing the size and shape of the voids (smooth, flattish floors and digitate to irregular wavy roofs) are pseudo-'stromatactoid' masses of pale-yellow weathering, pale-brown dolomite. Although in outcrop and in slabbed hand specimen they resemble voids filled by geopetal sediment, microscopically they consist of 50 to 80 μm dolomite rhombs replacing the host micrite. Locally, micrite remnants, some containing fine, spar-filled tubular fenestra, are enclosed in the dolomite. Clusters of small 150 μm ostracodes occur within and straddle the sharp dolomite/micrite contact.

Finally, early and late fracture porosity occurs. Both are filled by blocky spar but early fractures are buckled and broken into segments by compaction.

*c) Bioclastic Wackestone–Packstone Lithofacies.* This association is composed of rubbly weathering, well-bedded, fossiliferous and bioturbated, dark-grey limestones. Weathering reveals the 30- to 100-cm-thick beds consist of wavy thin beds separated by numerous argillaceous seams.

Although there is a wide spectrum of rock types ranging from mudstone to grainstone, the dominant lithology is burrowed wackestone and packstone. Packstones composed essentially of bioclasts and peloids are associated with some spicular mudstones toward the base of the association at Gargamelle Cove. There, at the base of the association, overlying the cyclic association, is also a crossbedded grainstone more than 60 cm thick (Plate 61). The crossbeds, which have an apparent direction to the southwest, are 15 cm thick and up to 1.5 m long.

Upward, the succession is dominated by the burrowed wackestones, which are composed of micrite, bioclasts and micritic peloids. Some wackestone beds are better cemented and resistant to weathering. Microscopically, they prove to be more peloidal than other wackestones and contain abundant calcite cemented fenestra. Beds and lenses of grainstone up to 15 cm thick occur sporadically throughout the rest of the section. High-spired and planispired gastropods, particularly *Maclurites*, and straight cephalopods are common in the limestones. Cephalopods up to 30 cm in length and several centimetres wide occur. Other organisms include brachiopods, trilobites, ostracodes, pelmatozoans, bryozoans

**Plate 61.** *Crossbedding in epigenetic dolostone that replaces Table Point Formation limestone at Gargamelle Cove.*

and sponges, the latter forming the main framework organisms of small bioherms that grew on and are fringed by grainstones composed of skeletal and intraclastic detritus (Klappa and James, 1980).

Bioturbated wackestones that dominate the association are composed essentially of micrite, which locally has a indistinct peloidal fabric, and skeletal and algal grains. Skeletal components, which comprise 15 to 20 percent of the rock and also include brachiopods, are similar to the those of packstones. They can be variable in some beds or restricted to ostracods and crinoids in others. Micritization of grains is common. *Girvanella* is widespread in the micritized grains, but also encrusts in a ball of wool-fashion skeletal remains. It also forms distinct cigar-shaped intraclasts. The micrite matrix contains clots and numerous solitary and clustered tubules of calcareous algae.

Burrow sediment is recrystallized to 10 to 30 μm microspar liberally enclosing 10 to 30 μm dolomite rhombs. Dolomite layers pick out burrow margins (intramuros dolomite of Haywick and James 1984); some burrows contain clusters of inwardly narrowing, barrel-shaped calcite crystals (100 by 400 μm in size) that protrude inward from the burrow margin.

Microscopically, the packstones from the base of the formation consist of peloidal and bioclastic–intraclastic–peloidal layers that have been disrupted somewhat by burrowing organisms. Peloid layers consist of 120 to 700 μm dark micritic peloids set in micrite or microspar. Skeletal grains, which are uncommon in the peloid packstones, are the same as those found more liberally in the bioclastic–intraclastic–peloidal packstone domains. They include ostracode, gastropod, trilobite, bryozoa and crinoid remains. Many grains have micritized edges. The micrite of some

grains contains *Girvanella* tubules. Fibrous isopachous cements occur in bryozoa zooecia and within whole ostracode carapaces. Gastropods are mostly replaced by coarse blocky spar. *Nuia* grains, 30 by 100 μm in size, are scattered in amongst the dark micritic peloids. Intraclasts in the packstone include skeletal wackstone, peloidal wackestone permeated by vermicular spar-filled fenestra and lime mudstone. The mud matrix of the packstone is now largely obcured by recrystallization to microspar and by coarser neomorphic spar. Some layers are dolomitized by 60 to 80 μm dolomite spar. Authigenic quartz crystals and patchy silica cements within intraparticle porosity occur sporadically.

The spicular mudstone that is interbedded with the packstone consists of single and forked microspar spicules floating within micrite. Articulated ostracod shells filled by clear equant cement, or when collapsed by micrite, are scattered sparsely in the mudstone. Gastropods are outlined by micrite envelopes and replaced by clear blocky spar as is general with Table Point limestones. Lensoid shrinkage(?) cracks crosscut the mudstone and are healed by 300 μm blocky spar.

Grainy beds in the formation are dominantly composed of 20 to 200 μm sized micritic peloids and micritic grains set in transparent, 15 to 50 μm spar. Scattered among the grains are some that show a spherulitic radiating fabric mostly rimming a micritic core. Although some of these grains reach 500 μm in diameter and resemble ooids, smaller grains, 170 to 300 μm in size, are cigar-shaped having a fibrous fringe around a hairline micrite core. They compare closely to the problematic micro-organism *Nuia*. Some micrite grains also contain *Girvanella*. Micritic rims are common around many skeletal grains. Most thin sections reveal small ostracodes, crinoids, bryozoans, calcispheres and gastropod remains. Some radial fibrous cements occur on and in skeletal remains and syntaxial rim cements are common on crinoid platelets.

The crossbedded grainstone that occurs at the base of the association at Gargamelle Cove consists of very well-sorted, peloidal layers and moderately sorted, peloidal–bioclastic layers. Broken skeletal grains include bryozoa, ostracodes (having early micrite cement attached), sponges, crinoids, and rare trilobite remains. The algae *Halysis* and *Nuia* are minor grains in the lime sand. The grainstone is cemented by 30 to 350 μm xenotopic, neomorphic spar. The grainstone beds near the base of the association are not so well sorted, lack crossbeds and contain molluscan particles as well as micrite and *Girvanella* mudstone intraclasts.

Sponge mounds occur scattered on a bedding plane just north of Pointe Riche lighthouse and on the north shore of Gargamelle Cove. They were recently described by Klappa and James (1980) as part of a larger study of these bioherms in the Table Head Group of western Newfoundland. The spherical mounds, which are 1 to 2 m in diameter and up to 35 cm thick, consist of two kinds. Klappa and James (1980) describe mud mounds without recognizable sponges and mounds of skeletal floatstone and bindstone composed of sponges, other skeletal organisms and mud-sized sediment. The following description of the mounds is summarized from the work of Klappa and James (1980).

Mounds without sponges are mostly wackestones rich in calcareous algae and sponge spicules and exhibiting internally a fine reticulate spongy fabric. However, the skeletal bioherms are dominated by sponges of varying shapes that are identified as *Archaeoscyphia*, *Hudsonospongia*, *Anthaspidella* and *Eospongia*. They are associated with *Pulchrilamina*, a variety of morphological habits of the bryozoan *Eridotrypa*, common pelmatozoans and calcareous algae. The latter include *Solenopora*, *Hedstroemia*, *Girvanella* and *Halysis* as well as *Nuia*, which may possibly be a codiacian algae. Trilobites, ostracodes, gastropods and brachiopods occur embedded in or on the mounds.

The mounds developed upon ripple-marked, bioclastic (pelmatozoan) grainstones, which were stabilized by pelmatozoan holdfasts. This, the first of four stages of growth identified by Klappa and James (1980), they called the pioneer stage. The succeeding colonization and diversification stages occurred as branching and encrusting sponges colonized the grainy substrate and then diversified together with other organisms to form the main body of the mounds. Bafflestones, floatstones and framestones compose the mounds at this stage. Large but few, encrusting and laminated organisms colonized the top of the mounds. The resulting bindstones and floatstones form the last 'domination' stage of the bioherm growth.

Bioclastic grainstones fringe the bioherms passing into thinly bedded, bioturbated wackestones and packstones. The grainstone beds have more diverse skeletal components than grainstone lenses and beds distributed throughout the association. They include parts of most of the organisms listed for the formation but also include significant amounts of the calcareous algae, *Halysis* and *Girvanella*. *Girvanella* especially occurs in intraclasts as well as in micitic envelopes that enclose other skeletal remains. Many skeletal remains were degraded by micritization, and also cemented by early micrite and microspar cements prior to ripup and incorporation in the grainstone. Some whole ostracodes contain bushes of 50 μm micrite peloids surrounded in the centre of the chambers by granular microspar cement. Fragments of mound-building organisms such as bryozoa and sponge remains, the latter not readily visible in thin section, are common. Many bioclasts also show dolomitization. Rare skeletal wackestone intraclasts also occur. The grainstone is cemented by 0.15- to 1.0-mm blocky spar. Neomorphism is common.

Overlying the mounds and wackestone at both Pointe Riche and St. John Island, Klappa and James (1980) describe a thin-burrowed lime mudstone having spar cemented burrows and an intraclastic veneer. This lies beneath a thick sequence of burrowed, thin-bedded lime mudstones having thin dolostone layers. Wavy to planar lamination and some mudcracks occur in the sequence.

Also peculiar to the association is a number of limestone breccias. They are composed of angular to rounded, unsorted

and disoriented limestone lumps set in a dark, argillaceous matrix of micrite and scattered quartz and feldspar silt. The breccias, which reach at least 1 m in thickness, occur along the shore from Gargamelle Cove to Pointe Riche and on the point south of Gargamelle Cove. They also occur on the northeast shore of River of Ponds Lake. Although the breccias near Gargamelle Cove may belong to one stratigraphic unit, lying approximately 40 m (Stouge, 1980) from the base, the stratigraphic position of the bed on River of Ponds Lake is not known. No contacts are exposed and they may be underlain by Black Cove shales and Goose Tickle flysch and hence be part of the Daniel's Harbour member (see Stenzel *et al.*, 1990).

The clasts, which are 1 to 15 cm (mostly up to 5 cm) in cross-section, compare well to the typical Table Point limestones, including massive, fossiliferous, bioturbated and clotted dark-grey lime wackestones. Some platy clasts of lime mudstone also occur. The unit at Gargamelle Cove has both obscure gradational bases and also crosscutting and frequently highly irregular contact relationships with underlying bedded limestones (Plate 62). Both styles of contact occur on the point south of Gargamelle Cove where, in places, the breccia appears to grade laterally into bedded limestone. A hummocky top is possible for the bed near Gargamelle Cove. The form is accentuated by weathering however, and nowhere is the upper contact well exposed. However, at River of Ponds Lake, the top of the bed is flat and overlain by a 1- to 2-cm-thick bed of laminated, dolomitic lime mudstone.

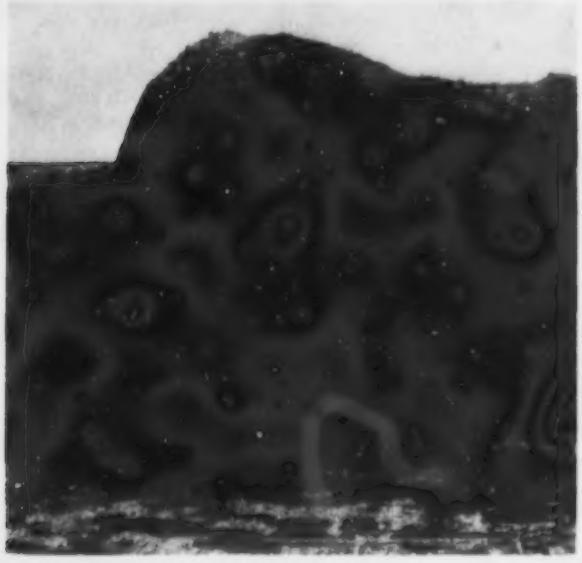


**Plate 62.** *Limestone breccia (above hammer) resting upon well-bedded Table Point Formation limestone, on the point south of Gargamelle Cove.*

*Age*

Rocks of Table Point Formation are Whiterock in age belonging to Zone M (Anomalorthis Zone) of Ross (1970).

*Depositional Environment*

The rocks of the Table Point Formation in the map area are part of the record of Llanvirn transgression of the Newfoundland platform. The basal cyclic and sporadically developed fenestral limestone-facies associations are essentially deposits laid down nearby or on carbonate tidal mudflats. These deposits were then superceded by massive, well-bedded, fossiliferous limestones that accumulated in a shallow, open, subtidal shelf sea. Distribution and thickness variations of basal peritidal strata hints that there were positive areas on the shelf that controlled facies distribution and thickness as the Llanvirn sea first encroached onto the platform. *In situ* formation of limestone breccia on the shelf suggests that the platform was tectonically unstable.

Of the two lowest facies associations, the cyclic association, which is preserved best near Port au Choix contains features compatible with a tidal-flat origin. Beds and sequences composed of basal massive–nodular subtidal limestone capped by laminated lime mudstone and rarely dolostone are very similar to the shallowing-upward muddy, low-energy tidal-flat sequences of James (1984). Individual components in the sequences, such as micritic peloids, lamination, small to large fenestra, rare mudcracks and low-density faunas restricted to ostracodes support a tidal-flat environment. The laminated limestones, consisting of layers of peloidal–fenestral fabric alternating with dense micritic layers, are characteristic of algal mat (Monty and Hardie, 1976; Pratt, 1982a). Allochthonous micritic peloids, mud and shells were carried by currents onto the tidal flat and bound by filamentous algae. Intergranular, vertical fenestra probably formed within the mats where filaments decayed (Monty, 1976; Pratt, 1982). The larger irregular and laminar fenestra that are common in the facies toward the tops of shallowing-upward sequences probably formed as a result of gas bubbles, bacterial decay of algal mat, lateral expansion of actively growing mat, shrinkage due to desiccation, and lithification (Monty, 1976; Grover and Read, 1978). Fine tubular fenestra likely preserve the activity of burrowing organisms (Grover and Read, 1978). The largest fenestra, some of which crosscut shells and other fabrics, were formed by dissolution of the host rock and enlargement of existing voids by infiltration of undersaturated freshwaters through the fenestral mudrocks. Freshwater vadose and phreatic diagenesis in these voids is supported by the presence of vadose silts, pendant cements and abundance of equant spar cements (Dunham, 1969; Grover and Read, 1978; Longman, 1980). The prevalence of fenestra within the mudrocks of the facies points to sufficient early lithification to support the cavity's roof within the peloidal framework.

However, in some beds, the largest fenestra are closed by a coarse fibrous cement. Fibrous aragonitic and high-Mg calcite cements are commonly indicative of marine cementation (James *et al.*, 1976; Longman, 1980; Flugel, 1982). The cement described here, however, may be recrystallized sometime after the formation and cementation of fractures but before stylolitization. The coarse fibrous cement may have formed by recrystallization of fine acicular

fibrous bundles as proposed by Kendall and Tucker (1973) and Bathurst (1982) for fascicular fibrous calcite and radiaxial fibrous mosaic cements. However, more recently Sandberg (1985) and Kendall (1985) has argued that these cements are in fact primary marine cements precipitated in cavities within the marine phreatic zone.

Evidence for meteoric vadose diagenesis, plus the absence of evaporites, low-dolomite content and general lack of mudcracks suggest a humid climatic regime during the accumulation of the tidal-flat deposits. The same interpretation is advocated by Grover and Read (1978) for the remarkably similar fenestral limestones of the Chazy Newmarket Limestone of southwest Virginia.

The importance of fenestral fabrics and other features in the lime mudstone of the fenestral limestone-facies association suggest a comparable humid, peritidal sedimentary setting to the cyclic association. However, some differences do occur. Although cyclic sequences are not obvious and different fenestral layers are generally intercalated, some beds are capped by laminar fenestral limestones indicative of periodic shallowing upward. Also, although the fenestral-rich mudstones host only ostracodes, the burrowed subtidal layers also contain gastropods and cephalopods suggesting a less-restricted shelf setting and access of the peritidal setting to the open-shelf sea. The importance of *Girvanella* and *Renalcis* as major components of the fenestral mudrocks suggests that they are nonlaminated cryptalgal deposits.

The prominance of 'stromatactoid' voids in the mudstones of this facies is interesting. Shape, internal sediment and fibrous cements compare well with the stromatactis cavities of Bathurst (1982). Bathurst (1982) advocates that the cavities are formed in subtidal mudrock by a multiple process of early lithification of sediment, winnowing of unconsolidated sediment; collapse and breakup of crusts and then later marine cementation of cavities. The voids described here, however, were clearly formed in shallow subtidal to intertidal muds that have a signficiant algal component and possibly framework. This is not too surprising since Monty (1976, page 221), discussing the formation of fenestra in cryptalgal deposits, suggested that 'stromactactoid' voids might be expected to form in algal mats that were not calcified and consequently decayed. Pratt (1982a) also has strongly argued that nonlaminated cryptalgal frameworks can readily produce the structural features of lower Paleozoic mud mounds including the enclosed stromatactis cavities.

The association of 'stromactactoid' voids in peritidal mudrocks of the Table Point Formation plainly suggests that the structures can form in sites other than mud mounds of deeper water shelf-settings as proposed by Bathurst (1982). It is probably premature to speculate that the fenestral limestone association of the Table Point Formation represents shallow-water mud-mound complexs. In the map area, the basal cyclic member is overlain by fenestral limestones near River of Ponds but by subtidal limestones of the bioclastic wackestone–packstone facies association elsewhere. This local geographic distribution of the association near River of Ponds may suggest that the facies association formed as a mud-mound within a shallow-shelf sea. Similar lateral distribution of the two facies has recently been mapped in the Daniels Harbour area (Knight, 1986) suggesting that peritidal mud mounds (islands) could have been prominent features of the shallow, early Middle Ordovician shelf. Further work on the Great Northern Peninsula (Knight, unpublished data, 1986) suggests that the facies may, in part, relate to the distribution of highs and lows on the faulted St. George Unconformity, since the fenestral limestone facies appears to occur in distinct belts between topographic highs on the unconformity.

The final facies associations, characterized by wackestones and packstones, with a diverse skeletal fauna and widespread burrowing, were deposited in an unrestricted, generally low-energy shelf sea. Besides a benthonic fauna of molluscs, brachiopods and arthopods, the sea bottom also hosted crinoids, isolated sponges and for the first time on Newfoundland's Ordovician shelf, bryozoans. Sponges, bryozoans and crinoids flourished locally on the shelf forming small biohermal mounds, after the organisms had colonized storm-generated pelmatozoan grainstone substrates (Klappa and James, 1980). Rock types and structures associated with the bioherms such as grainstone fringes, spar-cemented burrows, intraclastic veneer, wavy to planar lamination and some mudcracks suggest that the bioherms were constructed in shallow water with accretion of overlying sediment into the intertidal zone. Wave action reworked biohermal material and the wavy laminated dolomitic lime mudstone associated with some mudcracked beds were deposited in a tidal-flat setting.

The origin of the brecciated limestone beds within the bioclastic wackestone–packstone facies is still an enigma. The angular form of the clasts suggests that many of the beds were partly lithified. However, since the clasts are suspended in a silty micrite matrix, it is probable that the lithified layers were intercalated with soft lime mud. Sharp to transitional basal boundaries and possible hummocky to definitely planar tops, the latter overlain by laminated dolomitic lime mudstone, suggest the rock formed *in situ* at the surface of the sea floor. Earth tremors may have served to destroy the coherence of recently deposited bottom sediments. Early marine cementation produced lithified crusts that broke up into the clasts, which were suspended within unconsolidated lime mud. Local gradational boundaries suggest that mass transport has been negligible. Lack of evidence for vadose diagenesis appears to rule out that the deposits formed as a result of sudden emergence of the shelf bottom and subsequent mass wastage.

# DEPOSITS OF UNKNOWN AGE AND ORIGIN

## Torrent River Breccia

### *Description*

A coarse rock matrix breccia of problematic age and origin occurs along the Torrent River for 1 km just

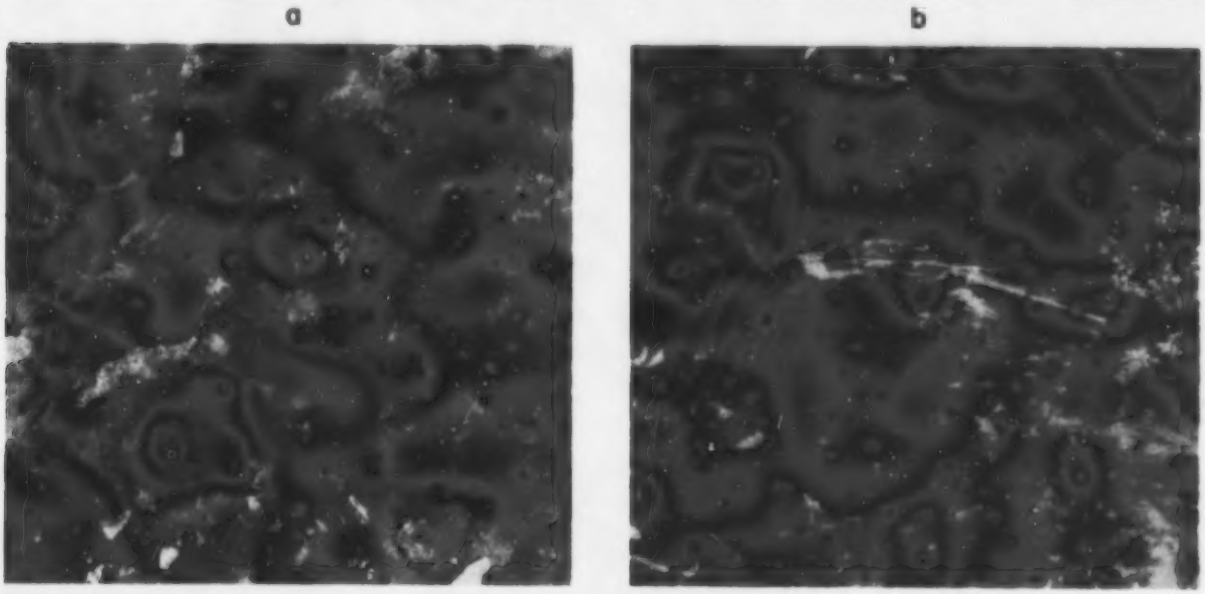



**Plate 63.** *(a and b) Torrent River breccia consisting mostly of dolostone clasts of the Petit Jardin Formation set in a quartz sand and dolomite matrix, Torrent River. Here the breccia is overlain by Hawke Bay sandstone (b).*

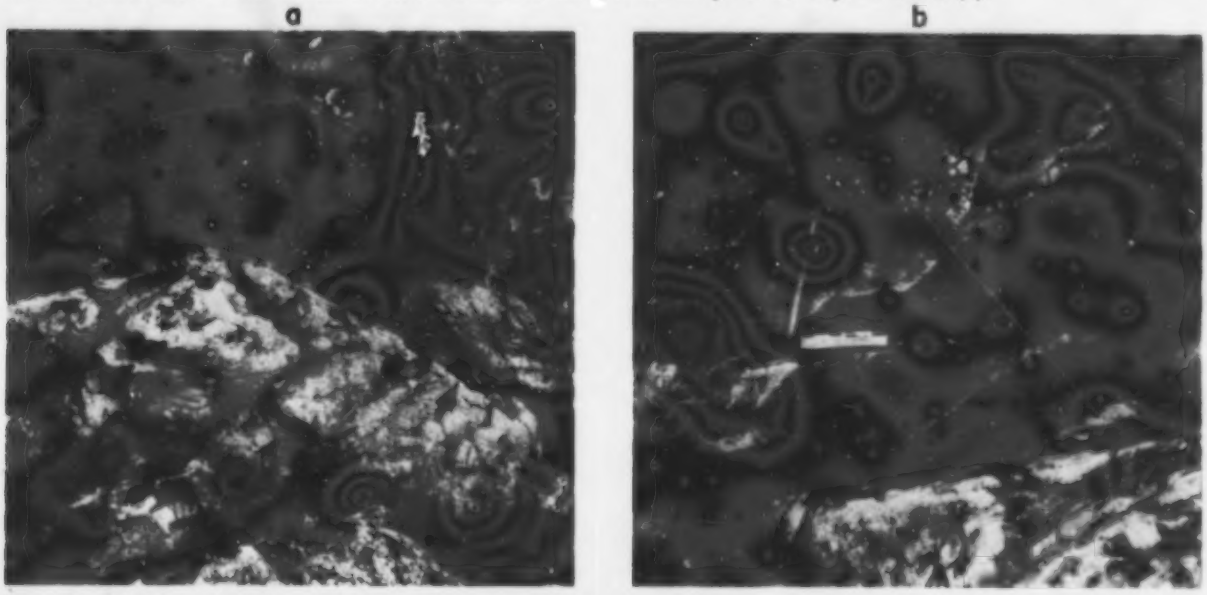



**Plate 64.** *(a) Joint- or fault-controlled margin (arrows) of the Torrent River breccia against dolostone beds of the Petit Jardin Formation; (b) a narrow fissure (by the hammer) filled by finer rock breccia is seen cutting dolostone above the breccia body.*

downstream of Pikes Feeder Pond (Plates 63 and 64). The breccia, composed mostly of dolostone blocks (Plate 63a) and sand- and granule-sized fragments, is set in a matrix of quartz sand grains. The breccia is bounded by quartz arenites of the Hawke Bay Formation to the southeast and dolostone of the Petit Jardin Formation to the northwest. This suggests the breccia is developed along the trace of a northeast-trending fault. The breccia lacks any structures such as fractures to suggest that it was produced by, or affected by, fault movements.

Three outcrops occur along the river. In the two to the northeast, the breccia is apparently overlain by gently warped beds of Hawke Bay Formation (Plate 63b). The breccia here is dominated by blocks of up to 30 cm in size of thin-bedded, laminated, massive, stylolitic, mottled, oolitic and vuggy dolostone. Some fragments of chert, phosphatic sandstone, rusty-weathering, laminated dolomitic sandstone, bioturbated sandstones and white quartz arenite also occur. They are set in an olive green, sandy dolomite matrix. Only immediately beneath the overlying bedded quartz arenite are fragments of Hawke Bay Formation common. Locally, the top of the

deposit contains layers up to 5 cm thick of granular sandstone having an indistinct lamination. The matrix of the breccia at these localities is rich in rounded quartz and microcline sand grains in fine dolomite mud.

The third outcrop, which lies downstream of the others, exposes the northwestern side of the breccia (Plates 64a and b). The contact is a near vertical wall trending 205°, cross-cutting dolostone beds that strike 068° and dip 10° to the south. The rock breccia is here composed only of dolostone fragments set in a dark-brown dolomite mud matrix and yellow spar cement. A few siliciclastic silt grains occur. The rock matrix breccia is bordered by a fracture breccia of slightly displaced, interlocking dolostone fragments and dolomite veins. Beds from the top of the fracture breccia visibly peel off into the rock matrix breccia. Narrow fissures that trend 210°, parallel to the main breccia–wall-rock contact, cut the bedded dolostones a few metres from the breccia. The fissures are filled by fine breccia.

### *Interpretation*

Although the breccia appears to stratigraphically underlie quartz arenites of the Hawke Bay Formation, the sharp vertical contact with bedded Petit Jardin dolostones along the northwest side of the breccia suggests that the breccia is a cavern breccia. The cavern appears to have formed along a northeast-trending fault, which had juxtaposed the Lower Cambrian Hawke Bay Formation and the Upper Cambrian Petit Jardin Formation. The blocks that compose the breccia consist mostly of Petit Jardin Formation rocks. Rusty-weathering sandstones, burrowed sandstones and phosphatic sandstones suggest blocks of the top of the Hawke Bay Formation also occur. The white quartz arenites of the Hawke Bay Formation provide few clasts but there is abundant sandy matrix in the breccia developed beneath the Hawke Bay quartz arenite. This suggests that subterranean weathering may have decomposed beds of the formation and subterranean streams eroded the quartz arenite and transported the sand into the caverns that were filled by blocks of dolostone derived from the hanging wall of the fault.

The absence of crosscutting fractures in the breccia suggests that it formed after the last movements on the fault. This would imply the cavern breccia may be post-Devonian (Acadian) or post-Carboniferous in age.

# STRUCTURE

## INTRODUCTION

The map area, characterized by gently dipping, southward- and westward-younging strata is dominated by a braided and anastomosing network of long, curvilinear, north- to northeast-trending high-angle faults (Figure 11). The faults, which possess vertical displacements of tens to hundreds of metres, break the Paleozoic terrain up into a series of narrow (4 to 13 km wide), lensoid northeast-trending blocks and seperate it from the Precambrian Long Range Inlier. A number of west- and northwest-trending faults also occur in the area. They are of limited extent however, lacking great length and major vertical displacement.

Gently dipping homoclinal strata occur between faults. Dip of beds rarely exceeds 10° and most attitudes range from 2 to 5°. Very gentle, open warps occur also within fault blocks, generally plunging to the southwest by a few degrees. Immediately adjacent to faults, however, structural complexity locally intensifies so that bedding steepens markedly and may be inverted. Open to tight, decimetre-scale drag folds are also common and small thrust faults and zones of closely spaced fractures occur. Breccias are intermittently developed along some faults and blocks of exotic stratigraphy, unlike that of adjacent wall rocks, are trapped along the faults.

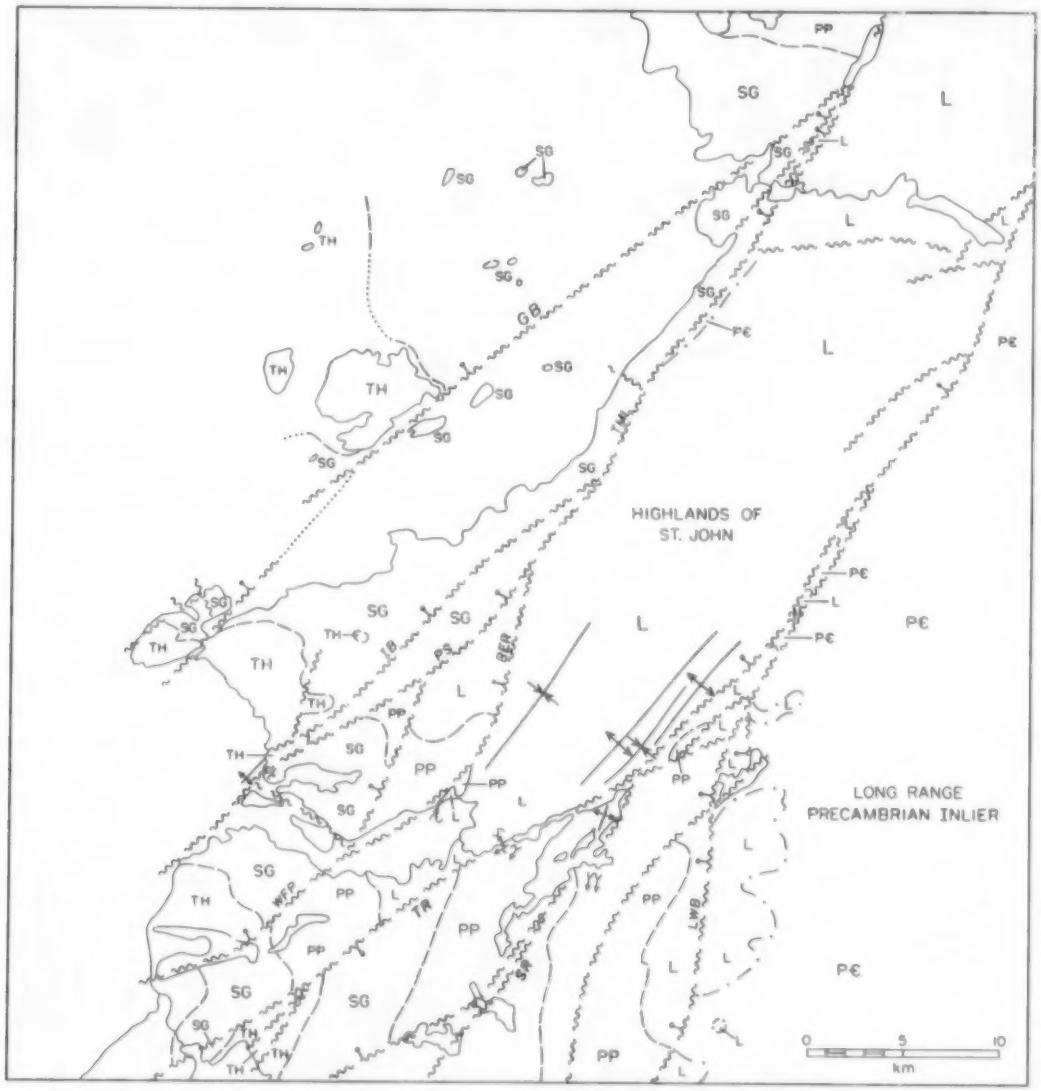
In the broadest sense, the map area is structurally divided into two by the Lady Worcester Brook fault (LWB), which seperates uplifted Precambrian basement of the Long Range Inlier to the east from downdropped Paleozoic autochthonous rocks to the west, a vertical throw of only 300 m. However, the greatest vertical displacement across a fault occurs along the Ten Mile Lake fault (TML), which is the dominant fault in the north of the area. It uplifts Precambrian granites and overlying Labrador Group to the east (the Highlands of St. John) over 1000 m, juxtaposing them against rocks of the St. George Group to the west. Following the fault to the southwest, this large vertical displacement is distributed between a number of faults that splay from the TML fault in the Port Saunders map area.

In the Port Saunders map area, the uplifted Highlands of St. John fault block forms a southwestward narrowing and plunging horst. It lies between the braided fault system of the TML fault and the Torrent River fault (TR), a major fault to the southeast. The TR fault traverses the middle of the map sheet northeastward to join with the Long Range boundary fault (LWB fault). Rocks west of the Ten Mile Lake braids consistently downthrow to the northwest. East of the TR fault, a wedge of rocks cut by splays of the TR Fault includes the Starvation Ridge fault (SR). Here, strata downsteps consistently southeastward.

## NORTHEAST-TRENDING FAULTS

Tabulation of structural details of the faults, their associated structures and presence or absence of breccias and structurally exotic blocks are listed in Table 4.

In general, the faults, which are readily delineated by field relationships supplemented by airphoto topographic lineaments, are narrow zones characterized by sharp fault planes (Plate 65) and minor subsidiary faults in nearby rocks. Small pockets of breccia are distributed along the faults. However, the faults may be characterized by a wide (up to 25 m) zone of intensely sheared and brecciated rock between




| | |
|---|---|
| GB | Good Bay Fault |
| IB | Ingornachoix Bay Fault |
| PS | Port Saunders Fault |
| TML | Ten Mile Lake Fault |
| WFP | Whale Factory Pond Fault |
| BER | Big East River Fault |
| TR | Torrent River Fault |
| LWB | Lady Worcester Brook Fault |
| SR | Starvation Ridge Fault |

| | |
|---|---|
| PE | Precambrian basement |
| L | Labrador Group |
| PP | Port au Port Group |
| SG | St. George Group |
| TH | Table Head Group |

*Fault, downthrow shown*

*Anticline, syncline*

*Minor folds*

*Unconformity*

*Stratigraphic or group contact, approximate, assumed*

**Figure 11.** *Map of main structural features of the Port Saunders, St. John Island, Castors River and Torrent River map areas.*

**Table 4.** Geometry and associated structural features of northeast-trending, curvilinear faults in the Port Saunders, St. John Island, Castors River and Torrent River map areas

| Name of Fault | Major Splays | Vertical Displacement (m) | Trend and Dip of Fault | Trend and Plunge of Drag Folds | Minor Fracture and Faults | Other Features |
|---|---|---|---|---|---|---|
| Lady Worcester Brook Fault (LWB) | Main Park Pond Fault | 30 m, downthrow to west | - | - | 342/62<br>350/40 | - |
| Torrent River Fault (TR) | Starvation Ridge Fault | 550 m in southwest<br>200-300 m in northeast<br>downthrow to southeast | 228/86°NW<br>235/65°NW | 214/10° to<br>236/10°SW | 050/32°SE<br>000/36 to 80°E | Overturned bedding in hanging wall; breccias locally; structurally exotic blocks; Boudins 012/56°N plunge. |
| Starvation Ridge Fault (SR) | | 550 m, downthrow | 222/55°NW | 035/2-6°NE | - | Overturned bedding in hanging wall; breccia locally; structurally exotic block. |
| Ten Mile Lake Fault (TML) | Big East River Whale Factory Pond Fault, Port Saunders, Ignornachoix Bay | 900-1200 m in the northeast; downthrow to the northwest<br>to the northwest | - | - | 020/56°NE | Breccia in footwall |
| Big East River Fault (BER) | - | 100 m, downthrow to the northwest | - | 057/7°NE<br>060/37°NE<br>220/2-4°SW | 030/64°SE fault<br>205/61°W fracture<br>032/64°SE fracture | Overturned Bedding and recumbent drag fold in footwall. |
| Port Saunders Fault (PS) | Whale Factory Pond Fault | 300 m in southwest<br>600 m in northwest<br>downthrow to northwest | 050/55°SE footwall<br>050/80°SE hanging wall | 226/7°SW footwall<br>210/10°SW to<br>021/2°NE and 243/6°W in hanging wall | 041/60°E fault<br>215/18°W fault<br>028/54°E fractures in fault zone | Slickensides pitching 45°SW on footwall; breccia beneath hanging wall. |
| Whale Factory Pond Fault (WFP) | - | 400 m downthrow to west | - | 239/7°SW<br>230/31°SW<br>225/27°SW | 220/66°NW<br>222/48°NW minor<br>225/27°NW faults | - |

hanging wall and footwall fault planes, as for example the Port Saunders fault (PS) at Two Hills Point (Plate 66). Fractures within this sheared zone were measured at 028° strike, 54°E dip and 250 to 275° strike, dip 78 to 75° dip. Assuming that these fractures form a conjugate set within the shear zone, the principal axis of stress, $\sigma_1$, is computed stereographically to have an average trend of 056° and average plunge of 45° northeast. The minimum axis of stress, $\sigma_3$, lies horizontal and trends 146° essentially at right angles to the trend, 050°, of the fault.

Offset of stratigraphic markers (Figure 11) in the map area is consistent with major vertical displacement upon reverse faults. However, it is peculiar that in the map area there are rarely major drag folds in hanging and footwalls that trend parallel to the faults and conform to the simple reverse fault model. Indeed, rocks that are folded opposite to that expected for a strict reverse fault situation, are encountered close to the PS, TR and SR faults.

**Plate 65.** *The exhumed footwall (arrow) of the Torrent River Fault, Round Steady, Torrent River. Dolostone of the Petit Jardin Formation composes the footwall.*

Minor drag folds close to the faults are generally gentle to open, having moderately dipping limbs. Recumbent folds are uncommon but do occur near the Big East River fault (BER) near Big Point, Hawkes Bay and at the east end of Long Steady near the TR fault. Axes of many drag folds strike between 020 and 060° and plunge generally to the southwest between 2 and 37°. Some folds plunge to the northeast and there are instances of folds that trend and plunge northwestward. The trend of the folds as a rule strikes obliquely into the main faults at an angle of up to 30°.

Stratigraphically exotic, structurally emplaced blocks occur along the TR and SR faults. On the southeast shore of Western Brook Pond, a fault-bound wedge along the SR fault consists of a narrow slice of Forteau Formation, which is vertical to inverted, younging northward, and in fault contact with a second narrow slice of moderately northward-dipping Petit Jardin dolostones. Both these structural slices are frozen in the SR fault zone between a footwall of Petit Jardin Formation to the south and a hanging wall of Hawke Bay Formation to the north. The wedge strikes parallel to the fault and is not so striking as an exotic block against the TR fault located on a small point on the north shore of Long Steady. Here, massive white sandstones of the Hawke Bay Formation dip 17° due west, quite discordant to all neighbouring rock trends. The sandstones occur in the footwall of the fault surrounded structurally by dolostones of the Petit Jardin Formation to the south, east and west and by the Forteau Formation to the north in the hanging wall of the TR fault.

Slickensides are not usually observed in many fault zones. Some poorly preserved slickensides measured on dolomite veins in the footwall of the PS fault pitch 45° to the southwest, suggesting some oblique slip movement on the fault. Boudinage of beds close to faults is also rare but does occur on the hanging wall of the TR fault opposite the fish ladder on the north side of river. The boudins, which trend 012° and plunge 56° north, are formed by thin sandstone beds intercalated with shales. The boudins occur within a metre of the fault plane but traced away from fault, the beds are cut by an imbricate set of closely spaced small faults. These faults trend up to 008° and dip at first at 60° east with dip decreasing to 38° as the fault is approached. Consistent normal slip of a few centimetres increases approaching the fault and eventually extension is sufficient to form boudins. Interbedded limestones at the same locality include thick, massive and thin, argillaceous, laminated beds in which inhomogeneous shear has folded the thin incompetent beds into intrafolial folds whose axes trend 242° and plunge 24° and other small folds that strike 215° and plunge 45° southwest.

The sum of these features suggests that the history of movements upon the northeast-trending faults is not simple. The trend and variable plunges of the drag folds, the strain ellipse computed from fractures within the PS fault zone, the extensional fractures and plunging boudins of the TR fault, the structurally emplaced exotic blocks wedged along some faults and some rare obliquely pitching slickensides suggest that strike and/or oblique slip has also occurred on the faults. The oblique trend of the drag folds to the main faults is consistent with right lateral slip (Moody and Hardy, 1966; Wilcox *et al.*, 1973). Extensional fractures and northeastward-plunging boudins in the hanging wall of the TR fault are also consistent with right handed displacement.

Simple geometric modelling of displacement across the PS fault also suggests some right lateral strike-slip movements. At Two Hills Point, the fault juxtaposes dolomitized Table Point limestones and dolomitized beds of the middle part of the Boat Harbour Formation, a maximum vertical slip of 300 m. The geometric model of the fault, which uses the present geographic offset of the St. George–Table Head contact on opposite sides of the fault and an average bedding dip of 7° to the south, suggests that at least 1000 to 1400 m of vertical slip should occur at this locality; this is a 700 to 1100 m difference between the slip in the theoretical model and that provided by field relationships. This anomaly is resolved, however, if right-lateral slip of approximately 4 km is postulated on the fault. Alternatively, the strata southeast of the fault might be affected by northwest- or west-trending folds or faults that downstep the strata northward whilst no structural modification occurs in the footwall to the northwest. One northwest-trending fault is likely through Keppel Harbour but it is bounded on both sides by rocks of the Boat Harbour Formation, and a vertical slip of less than 50 m is likely. In addition, there is little evidence of major folds in the hanging wall although some gentle warps do occur. Since interference by northwest- or west-trending structures in the hanging wall is probably minor, the role of strike-slip movements to explain the anomalous throw is strengthened.

Offset across the TR fault, however, is consistent with reverse slip and/or sinistral strike-slip displacement. This

**Plate 66.** *The Port Saunders Fault zone at Two Hills Point. Dolomitized Table Point limestone outcrops to the left. It is separated by a wide zone of sheared and brecciated dolostone (between arrows) in the hanging wall of the fault from gently warped dolostone of the Boat Harbour Formation. Prominent joints cut the Boat Harbour dolostone in the background.*

relationship, opposite of that on the PS fault would encourage cautious regard for reverse plus dextral movements on other faults. However, applying the simplified geometric modelling to offset of the boundary between the St. George and Port au Port groups across the TR fault, there is less than 200 m vertical difference between the larger theoretical displacement and that provided by real rock relationships. Poor exposure in inland areas obscuring faults and minor warps may well accommodate much of this discrepancy in throw.

## WEST- TO NORTHWEST-TRENDING FAULTS

West- to northwest-trending faults are known from the shoreline at Catoche Point and 2.5 km north of Barr'd Harbour. A northwest-trending fault is also postulated to trend along Keppel Harbour. Downthrow to both the southwest and the northeast occurs, but stratigraphic relationships either side of the faults suggest that vertical slip is rarely more than a few tens of metres.

The fault at Catoche Point lies along the south side of Catoche Island. It strikes 300 to 310°, dips 70 to 84° northeast in the west, and strikes 110°, dips 66° south at the east end of the outcrop. The fault continues southeast into Barbace Cove where it joins with another fault (concealed), which strikes southeast to Back Arm. The concealed fault is postulated to occur in the cove, since a linear zone of epigenetic dolostones replaces Catoche limestones on the east shore of the cove. At Catoche Point, the main fault is flanked to the south by a zone, several metres wide where the beds are gently warped and cut by numerous fractures and a number of smaller faults that mimic the direction and altitude of the main fault. Beds are downthrown to the south. However, horizontal slickensides on the main fault suggest right lateral slip and this is supported by small-scale elbows and roughness on the fault plane and by lenses of breccia along the fault plane. The best evidence is provided, however, by right-handed offset of three earlier, reverse faults that strike 045°, dip 75° east and that cut strata on Catoche Island and the mainland.

North of Barr'd Harbour, strata of the Watts Bight and Boat Harbour formations are cut by a number of west- to northwest-trending faults. The main fault is a 3-m-wide gauge of sheared dolostone that seperates downthrown Boat Harbour strata to the north from topmost Watts Bight strata to the south. The normal fault strikes 271° and dips 74° north. Several smaller faults occur in the hanging and footwalls. They include both normal and reverse faults that range in orientation from 110°, dip 40° to 57° south, north of the main fault, to 279°, dip 76° north, south of the main fault. Conodonts recovered from the Boat Harbour Formation in the area are typical of Fauna 1 (Stouge, 1982, personal communication, 1984) that's recovered low in the Boat Harbour Formation. This suggests that vertical slip here is no more than a few tens of metres.

## CONCLUSION

The structural history is essentially the dissection of the lower Paleozoic platform by northeast-trending faults. Large vertical throws across many of these faults suggest that mostly reverse slippage has occurred. Mild compressional stress caused uplift and westward overthrusting of both Precambrian basement and autochthonous lower Paleozoic rocks along the northeast-trending faults. The consistent southwestward younging of strata in the area, however, suggests that the faults cut a terrain that was already gently tilted southwestward.

The long curvilinear faults that braid and anastomose also have some characteristics of wrench faults. The evidence of

minor structures and structural relationships such as orientation and form of drag folds, slickensides, minor extensional fractures passing into boudins, exotic structural blocks, and offset of stratigraphic markers are all compatible with wrench faulting (Moody and Hill, 1956; Wilcox *et al.*, 1973). Structural relationships suggest that dextral movements occurred at least along portions of the Ten Mile Lake system, particularly where fault braids swing more east-northeastward. Lateral displacement of no more than 4 km is likely along the PS fault.

Compressional stress was applied to rocks in the northern part of the Humber tectonostratigraphic zone of western Newfoundland during Taconic and Acadian deformation (Williams, 1978b, 1979). During the Taconic phase, westward-directed thrusting and recumbent folding accompanied emplacement of the Taconic allochthons of Hare Bay and Humber Arm; whether the allochthons thrust over the Port Saunders area is not known but seems unlikely based upon low CAI values in the area (Stouge, 1986; Nowlan and Barnes, 1987). The later Acadian phase produced northeast-trending upright folds and high-angle faults in the Canada Bay area (Knight and Saltman, 1980). Acadian thrusting to low-angle reverse faulting of the Long Range Inlier over the lower Paleozoic platform is known 50 km to the south from Portland Creek to Bonne Bay (Knight, 1985; Williams *et al.*, 1985; Grenier and Cawood, 1988). It is, therefore, prudent to relate the dominant phase of reverse faulting in the map area to Acadian deformation. However, it has been shown that synsedimentary faults, trending northeast, already affected the platform during the late Arenig (see description of the Aguathuna Formation) and also likely influenced the manner in which the platform collapsed during the Middle Ordovician (Klappa *et al.*, 1980; Knight, 1985). Therefore, with major faults already established in the Paleozoic cover and probably rooted in Precambrian basement by the time the Taconic phase reached its climax, it is not sensible to neglect the possible influence of the older orogen on the platformal strata.

Grenier and Cawood (1988) have argued that the Ten Mile Lake fault, the Lady Worcester Brook fault and the Long Range fault are weakly emergent, steep thrusts related to Acadian deformation. Faults such as the Torrent River and Starvation Ridge faults are, however, interpreted as high-angle reverse faults. Their model involved abrupt abandonment of the sole thrust that occurs within the Grenville basement and rapid ramping to the surface as high-angle thrusts with decreasing displacement northward along the Northern Peninsula. In this model, the Precambrian inliers of the Long Range and to a lesser degree, Mount St. Margaret and Highlands of St. John are allochthonous. As has been already mentioned, however, true thrust relationships between basement and cover are only found south of Blue Mountain and Eastern Blue Pond (Bellburn map sheet). North of this location, the faults are all subvertical to vertical with mostly high-angle reverse displacement. The faults' definition and associated structures are everywhere fairly consistent suggesting a common origin and type i.e., reverse fault. The evidence for northeast-trending brittle fracturing deforming the Cambro-Ordovician platform at the earliest stages of the Taconian implies that high-angle faults already were in existence and were coupled to basement fault blocks before Acadian deformation. Indeed evidence for Late Precambrian–Early Cambrian basement faults influencing sedimentation during deposition of the Labrador Group (see discussion, Labrador Group; James *et al.*, 1989) implies very long-lived high-angle faults rooted in the basement. Bearing this in mind, it is sensible to be cautious invoking the thrust model in the Port Saunders area and northward because reactivation of early faults would be probable.

Some wrench faulting along the northeast-trending faults is probable since both Devonian and Carboniferous transcurrent movements are postulated for the Canadian Appalachians. Sinistral faulting is postulated upon major fault zones in western Newfoundland during the Devonian by Chorlton (*in* Chorlton and Knight, 1983). However, dextral movements of large proportion (20 to 120 km) are proposed in several studies of Carboniferous sedimentary basins in Maritime Canada and western Newfoundland (Hyde, 1979; Bradley, 1982; Knight, 1983). The lower Paleozoic platform lying 60 km northwest of the Cabot Fault system, the main zone of Variscan deformation and lateral slip in western Newfoundland, may have been mostly sheltered from the main locus of shear. Nonetheless, it likely accommodated Carboniferous stress by minor slip along the northeast faults.

Northwest- and west-trending faults in the area are interpreted as antithetic faults that formed during reverse and strike-slip movements. They played a minor role in the distribution of rock units and field relationships but relieved the strain in the Paleozoic strata as deformation proceeded.

# ECONOMIC GEOLOGY

## INTRODUCTION

Rocks in the map area host a number of galena, sphalerite and pyrite showings within dolostones of the Petit Jardin, Boat Harbour and Table Point formations. Traces of zinc mineralization occur in the dolostones of the March Point Formation. Minor barite and fluorite also occur within the map area, in the Petit Jardin and Boat Harbour formations.

No mineralization has so far been found in strata of the Catoche Formation equivalent to that hosting the Daniels Harbour zinc mine. Suitable host rocks occur plentifully in the map area and some mild zinc anomalies outlined by soils and till geochemisty occur over the unit.

The area with its sheltered deep-water harbour at Hawkes Bay, the site of storage and loading facilities for zinc concentrates from Newfoundland Zinc Mines, also hosts large reserves of industrial minerals, particularly siliceous sandstones of the Hawke Bay Formation. Shales in the Forteau Formation contain high potassium values and form a potential source of agricultural potash.

## HISTORY OF EXPLORATION

The earliest record of mineral exploration in the area is provided by a report (possibly for the government of the day) of a pyrite showing on Round Head Island, St. John Bay (Maher, 1917). The geographic isolation of the map area at this time probably contributed to the long hiatus of mineral exploration that followed for the next 50 years. Foley (1937) described minor chalcopyrite–pyrite–marcasite mineralization within amphibolite and schists in the Long Range Precambrian east of Pikes Feeder and Black Stag ponds (Torrent River map sheet) but no metallic mineralization was noted in lower Paleozoic sediments during this long period of time.

The first hint that base-metal minerals were contained in Paleozoic rocks of the area came when road crews, constructing a woods road for the Bowater Paper Company Limited west of Pikes Feeder Pond, chanced to uncover galena in Upper Cambrian dolostones (Nelson, 1955). This showing later became the focus of further exploration by New Jersey Zinc Exploration Company (NJZ) (Shearer, 1964; Beckett, 1966). NJZ undertook soil and stream geochemistry and trenching to evaluate the showing. A small sphalerite–pyrite showing on the sea shore north of Eddies Cove West (Woodard, 1957) was also investigated by NJZ (Shearer, 1964; Beckett, 1966). Shearer (1964) also conducted mapping and soil and stream geochemistry in Doctors Brook valley, in the lowlands beneath the scarp of the South Summit of the Highlands of St. John, and in the bogs and hilly country of two areas between Big East and Torrent rivers. No significant geochemical targets were identified although some anomalous zinc values were documented in the lowlands near the Highlands of St. John.

The Port au Choix–Pointe Riche peninsulas and the area east of Port au Choix and north of Hawkes Bay were explored sporadically, as part of a Brinex Limited concession, throughout the 1960 and 1970's. Report of a sphalerite–galena boulder at the head of Port Saunders Bay by Helgi Johnson (quoted by Coope and van de Poll, 1965) gave impetus to exploration of this area. The area, which is underlain by plentiful exposure and subcrop of Catoche dolomites has, however, given few encouraging signs of mineralization. Newmont Mining Company (Coope and van de Poll, 1965) began reconnaissance mapping and geochemical sampling of the Brinex concession. Although they were sufficiently discouraged to recommend no further work on the concession, interest was renewed again in the 1970's. Stratigraphic reassessment of the area confirmed the similarities but not the differences of its lithostratigraphy to that at Daniels Harbour (Kluyver, 1973). Geochemical surveys for Brinex by Govett (1974) and independently by the Newfoundland Department of Mines and Energy (Davenport *et al.*, 1974a, b) showed the presence of metal anomalies within the concession area. There followed a drilling program (Lopej and Edwards, 1976) that found some very minor evidence of mineralization and a later program of deep-overburden geochemical sampling using a Pionjar drill (Smith, 1978; Ryder, 1979). The exploration effort culminated in a program of unsuccessful diamond drilling (Dickie and Lyn, 1979). These ventures were pursued jointly by Brinex and Riofinex and by Brinex, Riofinex and Freeport.

Galena and sphalerite showings first discovered on St. John Island by Helgi Johnson (quoted by Coope and van de Poll, 1965) have received little attention. Coope and van de Poll (1965) seem to imply that the showings occur in dolomites at the top of the St. George Group and not in secondary dolomites within the Table Head Group as correctly shown on recent regional maps (Cumming *in* Bostock *et al.*, 1983).

Elsewhere in the Port Saunders map area, exploration has been restricted to reconnaissance mapping and some drilling by Tecam Limited (1975). A group of eleven drillholes were sunk including a line of five widely spaced holes from Forked Feeder Pond to Island Pond. The holes intersected rocks of the Petit Jardin and Watts Bight formations. Two holes, which are interpreted here to have intersected oolitic limestones and dolostones of the middle stromatolite member of the Petit Jardin Formation, contain minor galena within fractures. No mineralization was recorded in the other six holes, two of which were collared in the secondary dolostones of the top of the Catoche Formation.

## MINERALIZATION IN CAMBRIAN CARBONATES

Galena and sphalerite occur principally in the dolostones (particularly of the middle stromatolite member) of the Petit Jardin Formation. Apart from the fracture-hosted galena already mentioned in drillholes near Forked Feeder Pond (Tecam Limited, 1975), the dolostones of the formation contain the best known, galena-sphalerite showing 1.1 km west of Pikes Feeder Pond (Grid Reference 50055 56086, NTS 121/10). Dolostones along Indian Steady, 2.4 km north of the Pikes Feeder Pond showing, contain vugs with barite. Minor barite also occurs in basal shaly dolostones along a north-pointing wood road (Grid Reference 49675 559635, NTS 121/11) just east of Big House Pond. Crystals of badly weathered sphalerite are sparsely disseminated in brown-weathering, dark-grey, vuggy dolostones of the Middle Cambrian March Point Formation along the same road and on a ridge west of Otter Pond (Grid Reference 4838 56034, NTS 121/11).

The Pikes Feeder Pond showing occurs in dolostones that dip almost due west at 4 to 10°. Several showings occur along a strike length of 1200 m in a bedded section that is 1.5 m thick. It is composed of buff-weathering, vuggy, structureless, finely crystalline, pale-grey vitreous dolostone that overlies dark-grey, oolitic dolostone. Slabbed samples of the pale-grey vuggy dolostone reveal some dark- and light-coloured crenulous laminae, which suggest the bed is stromatolitic. Galena, green-yellow sphalerite, chalcopyrite and pyrite occur at the main showing. Malachite staining and minor barite, not mentioned by Beckett (1966), also occur. Beckett (1966) estimated that galena averaged less than 2 percent and even less sphalerite was distributed over 60 cm in the showing. Locally, within this thickness, zones up to 8 cm thick occur

**Table 5.** Metal values of mineralized grab samples from the Pikes Feeder Pond and St. John Island showing

| Location | Rock Description | Cu % | Zn % | Pb % | Ag ppm | Total Iron As $Fe_2O_3$ % | Cd % |
|---|---|---|---|---|---|---|---|
| Pikes Feeder Pond Showing | PFP-1 Grey, fine dolostone with disseminated yellow green sphalerite | 0.03 | 12.08 | 0.02 | <0.1 | 0.84 | 0.46 |
| | PFP-2 Grey, fine dolostone with disseminated yellow green sphalerite | 0.03 | 11.82 | 0.18 | <0.1 | 0.84 | 0.43 |
| | PFP-3 Grey dolostone | 0.01 | 3.18 | 2.07 | <0.1 | 0.90 | 0.11 |
| | PFP-4 Grey, fine dolostone with coarse crystalline galena, locally in clots and as cements in hairline fractures | <0.01 | 0.14 | 18.83 | 1.4 | 0.84 | 0.08 |
| St. John Island DB-2(83) | Rusty, grey dolomite stockwork in limestone | 0.01 | 5.61 | | 1.9 | | 0.12 |

with up to 40 percent galena. Metal analyses of mineralized dolostone from the Pikes Feeder Pond showing are given in Table 5.

The mineralization occurs in fractures and within intercrystal porosity. The most obvious mineralization occurs in open spaces along an irregular fracture network in which galena, as fine streaks, coarse 5 mm crystals, and as massive clots, is the dominant mineral. Galena also occurs in layers parallel to bedding within the vuggy dolostone. Then, it is disseminated in intercrystal porosity and also forms small clots and laminae associated with the more important green-yellow sphalerite, which forms up to 5 percent of the rock over at least 20 cm. The mineralization is stratiform within or possibly replacing an original depositional fabric of cryptalgal origin. Ooids are replaced by galena in the lower oolitic dolostone (Beckett, 1966). Beckett (1966) also described some dark-brown sphalerite confined to joints that run across the zone. Microscopically, the yellow sphalerite that fills intergranular porosity is rimmed locally by dark sphalerite and in some vugs is enclosed by galena. Galena is clearly seen to fill porosity developed along fractures. Chalcopyrite also occurs close to the fractures.

Detailed geochemistry over the ridge hosting the showings showed that a geochemical anomaly coincided essentially with the known areal extent of mineralization (Figure 12). The survey employed Bloom's dithizone method to estimate cold extractable heavy metals. Reconnaissance regional geochemistry along cutlines and streams was also conducted over a large area northwest of Western Brook Pond and south of Middle Pond (Beckett, 1966). Moderately anomalous values were found in streams draining Petit Jardin dolostones south of Middle Pond. The area north of Western Brook Pond, which is largely underlain by the Forteau Formation, has mostly background metal values.

Beckett (1966) suggested that the mineralization was essentially strata-bound to the oolitic dolostone and the overlying bed of vuggy, finely crystalline pale-grey dolostone. He also described a heavily mineralized fracture zone with some post-mineralization movements cutting the main showing. The fracture is north trending and steeply eastward dipping. Sphalerite in intercrystalline porosity in the stromatolitic dolostone and later fracture-controlled galena and iron-rich sphalerite support Beckett's conclusions.

Lead isotope ratios of galena from the showing are typical of fairly primitive leads (Table 6). This compares to leads from other galena showings in Middle to Late Cambrian rocks on the Northern Peninsula (S. Swinden, personal communication, 1985).

Barite hosted by Petit Jardin dolostones at the upper end of Indian Steady consists of long, bladed white crystals. These were precipitated in open spaces together with rhombic dolomite; fine, clear quartz crystals also occur in the vugs. Extensive fractures, which are slightly mineralized, cut the dolostone and connect with the mineralized cavities. Barite on the woods road near Big House Pond consists of pink cockscomb crystals in vugs and coating joint surfaces. The barite occurs in the red, green and black shales that are interbedded within the dolostones near the base of the Petit Jardin Formation.

# MINERALIZATION IN THE ST. GEORGE GROUP

## Boat Harbour Formation

Mineralization in the Boat Harbour Formation is restricted to pyrite, marcasite and sphalerite in stratabound

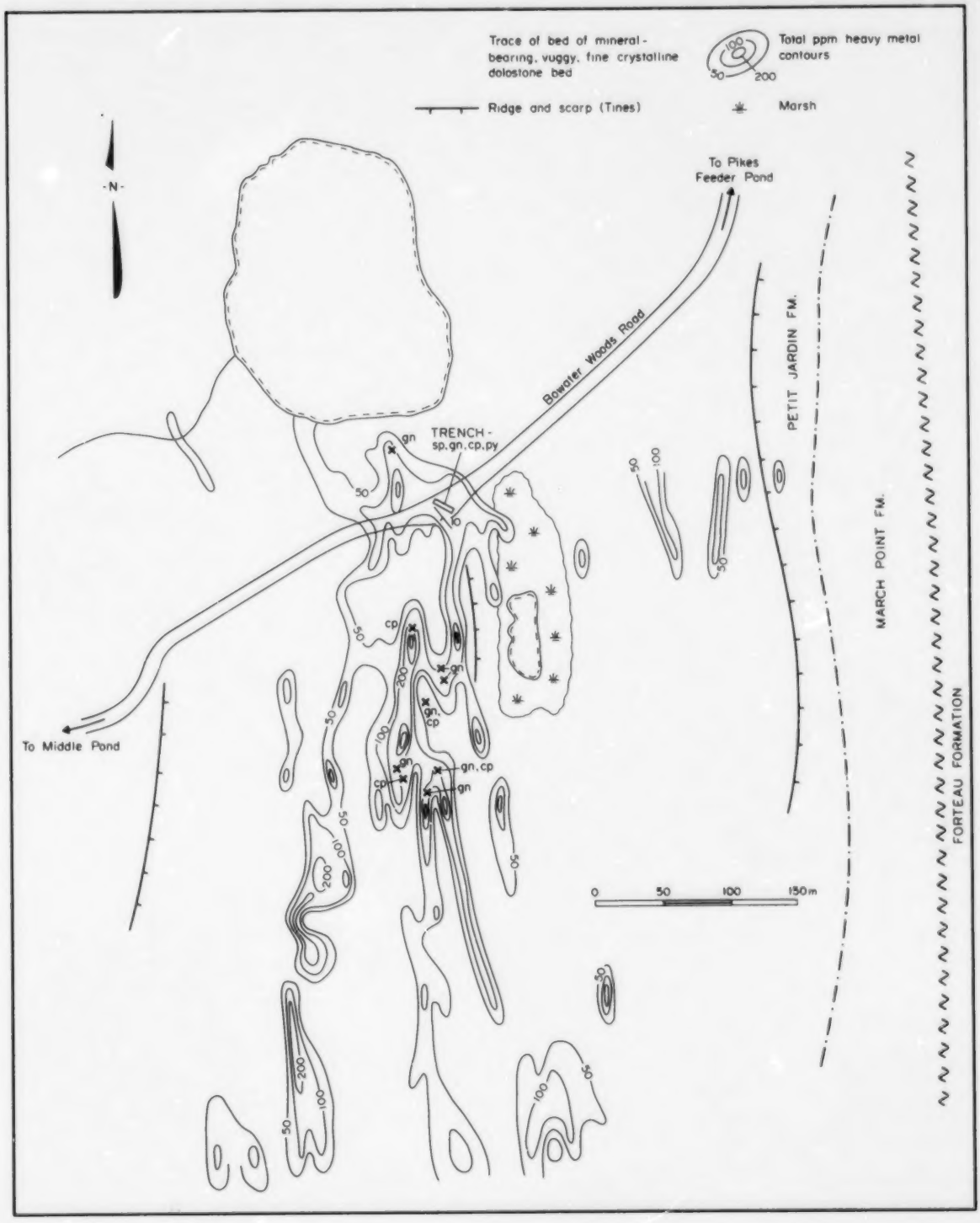



**Figure 12.** *Map of Pikes Feeder Pond showing the distribution of mineralization and geochemistry. Modified from Beckett (1966).*

**Table 6.** Lead isotope ratios from galena in the map area (contributed by S. Swinden, 1986)

| Locality | Host | Age | $^{206}Pb/^{204}Pb$ | $^{207}Pb/^{204}Pb$ | $^{208}Pb/^{204}Pb$ |
|---|---|---|---|---|---|
| Pikes Feeder Pond | Petit Jardin Fm. | U-CAMB | 17.294 | 15.388 | 37.871 |
| River of Ponds Lake | Table Point Fm. | M-ORD | 19.339 | 15.613 | 39.901 |
| St. John Island | Table Point Fm. | M-ORD | 18.506 | 15.568 | 39.299 |

breccias near the base of the formation. Blue fluorite with siderite, dolomite and quartz, fills vugs within a dolostone bed that caps a limestone bed of spectacular thrombolite mounds 1.5 km north of Eddies Cove West (Eddies Cove West, Unit 47, Appendix 1, Section 4). A few weathered crystals of sphalerite were found in epigenetic dolostones that replace a thrombolite mound bed at the point midway between Eddies Cove West and Fish Point.

Within the basal stratabound breccias, pyrite–marcasite and marcasite–pyrite–sphalerite showings occur on the northeast tip of Round Head Island (Grid Reference 4871 56286, NTS 12I/14) and in the cove 2.5 km north of Eddies Cove West (Grid Reference 4901 56237, NTS 12I/14) respectively.

The Round Head Island showing is situated near the high-tide mark of a low-cut intertidal bench. It consists of a brecciated dolostone at least 1.4 m thick and 20 m wide. Maher (1917) traced the zone 12 m inland from the intertidal zone where he seemed to imply that the breccia is replaced by massive ore. He suggested the mineralized body was 4 m thick but the stratabound breccia associated with beds that strike southwest and dip 4° to the west is unlikely to be more than 2 m thick.

The breccia, which probably formed by collapse after the dissolution of limestone, lies within 2 to 3 m of the base of the formation. It consists of blocks of white-weathering, mottled dolostone. Bronze-weathering, layered, acicular granular and prismatic, silvery grey to bronze pyrite and marcasite surround the fragments. Massive granular ore constituting 50 percent of the rock is common. Fissures that penetrate down into underlying unbrecciated dolostone are also cemented by pyrite. The mineralized zone is cut by several minor faults that strike 220° and dip 74° west. An analysis of the ore by Maher (1917) reported that the pyrite contained 39.9 percent iron, 46.04 percent sulphur and no arsenic.

The Eddies Cove West showing was trenched by NJZ in 1965. NJZ reported that it consists of nodules and open-space fillings of zoned sphalerite and pyrite (Shearer, 1964; Beckett, 1966) within brecciated dolostones. Unbrecciated rocks in the interval consist of dark-grey, massive and laminated, shaly dolostones as well as stromatolites. The mineralized nodules reported by Beckett (1966) were said to be 15 cm in diameter and distributed along a north-trending, steeply dipping vein, 15 to 30 cm wide and 4 m long. Marcasite and pyrite alone are common in the breccias. Also, he reported marcasite in the core of the nodules and open-space mineralization surrounded by a thin zone of iron-poor pale sphalerite, which is in turn enclosed by an outer zone of black (iron-rich) sphalerite. Pink and white sparry dolomite cements most remaining open space in the breccias. However, nodular ore was not found. The ore, which is principally composed of pyrite, forms over a width of about 10 m in a layer 1 m thick within a spar-cemented, dolostone breccia. Pyrite occurs as bands, fracture coatings, fracture fills, and replacement of breccia fragments. Sphalerite occurs as light- to dark-brown crystals in dolostone fragments and as dark red-brown coatings on pyrite, within clasts and in veins up to 0.5 cm wide.

Soil and stream geochemistry of the area inland of the showing failed to reveal any significantly anomalous metal values except those close to the showing. However, visible pyrite and badly weathered crystals of disseminated sphalerite were discovered in an interesting mounded pseudobreccia bed that replaces a thrombolitic limestone bed on the point 1 km to the west. The limestone–pseudobreccia sits within the bedded section that overlies the basal stratabound breccias.

## Catoche Formation

As reviewed in the history of exploration, the rocks of the formation are apparently devoid of significant mineralization. A rare crystal of amber sphalerite occurs in dolomite filled vugs within limestones of the Port au Choix section. No visible mineralization was encountered in drill core through Catoche dolomites east of Port au Choix although analysis of a pseudobreccia in one hole 5 km northeast of Port Saunders, gave 2650 ppm Pb and 3090 ppm Zn (Lopej and Edwards, 1976). Intersections of the pseudobreccia–dolomite interval in the Catoche Formation in the other 10 holes (Lopej and Edwards, 1976; Dickie and Lyn, 1979) were even less rewarding. Till and soil geochemistry showed ubiquitous background zinc values in the Brinex concession area with minor areas of anomalous zinc values, 4 km northeast of Port Saunders. Recent results of geochemical analysis of lake-sediment samples (Butler and Davenport, 1982) (reprocessing samples previously documented in an earlier regional studies by Davenport *et al.*, 1974a,b) show no anomalous Zn and Pb values in the Brinex concession area or in lakes over the Catoche Formation elsewhere in the area.

## Aguathuna Formation

Pyrite within fractures in breccias on Square Rock near St. John Island is the only mineralization found in the formation in the map area.

# MINERALIZATION IN THE TABLE HEAD GROUP

Four showings of galena and sphalerite occur within dolostones replacing Table Point Formation limestones on St. John Island (3 showings) and the northwest shore of River of Ponds Lake. All the mineralization occurs in epigenetic dolostones that formed along faults, fractures and minor warps within the limestones.

## St. John Island

Sphalerite ± galena occur along the south shore at Photographic Point and 1.7 km east of the point, and in a third group of showings on the west shore of Shorts Harbour. The mineralization in each showing occurs in brown- to yellow-weathering, strongly petroliferous, fine to medium crystalline, to salt-and-pepper textured, dark-grey dolostone. The dolostones have sharp crosscutting relationships with the host limestone.

At Photographic Point, epigenetic calcareous dolostone forms a tabular body, 3 m thick and 217 m wide, that is concordant to locally discordant within gently folded limestone beds. The dolomite is vuggy and locally resembles pseudobreccia. In the showing east of Photographic Point, the dolostones form a stockwork of subhorizontal to steeply inclined metre-wide dykes that crosscut and coalesce to enclose blocks of rubbly weathering limestone (Plate 67). The dykes are clearly related 1) to steep fractures that strike 070° and dip 58° southeast, 2) to eastward-dipping low-angle fractures, and 3) to fractures along bedding planes. In Shorts Harbour, several small bodies of mineralized dolomite occur in the core of a gentle anticlinal warp and as a fracture-controlled dyke oriented 042°; fossils from the host limestone confirm a Middle Ordovician age (D. Boyce, personal communication, 1983).

Although the dolostones are themselves vuggy, porosity was increased by rejuvenation of fractures that brecciated the dolostones and opened new fracture porosity. Slickensides are common on fractures and veins of dull grey, coarse dolospar were precipitated together with sphalerite and galena. Bitumen residues fill open spaces throughout the dolostones. Crystalline geopetal dolomite, geopetal sphalerite and laminated fine brown dolomite mud, fill spaces in the early dolostone. Tilting and brecciation of the geopetal layering in steeply dipping dolomite dykes suggest later movements.

At Photographic Point, sphalerite is disseminated as 0.1 to 1.0 cm crystals in the 'pseudobreccia like' dolostone. The black, dark red and amber sphalerite occurs in the upper 60 cm of the tabular dolostone and is concentrated along a bedding plane to low-angle fracture that trends 295 to 310° and dips 11 to 15° northeast. Zoned crystals of dark sphalerite surrounding amber occur. Pyrite occurs as clots and disseminations in the dolostones. It weathers to give a brownish stain to unmineralized parts of the dolostone body.

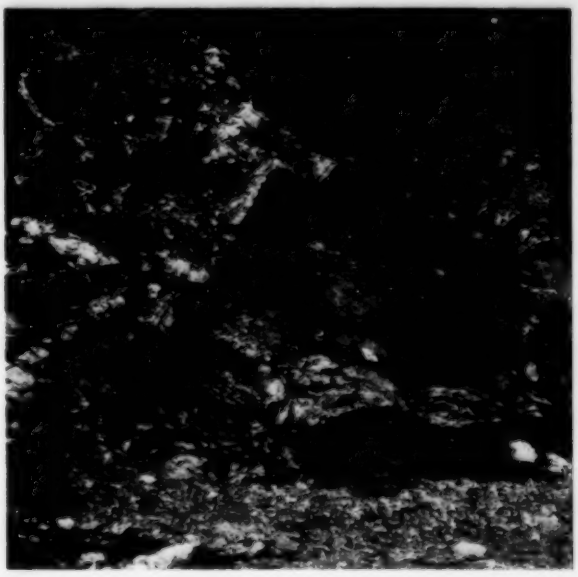


**Plate 67.** *A stockwork of mineralized dolomite veins cutting Table Point limestone, St. John Island. The dolomite contains sphalerite and galena.*

White to pink dolomite spar lines fracture and diagenetic porosity.

East of Photographic Point, the mineralization is mostly confined to narrow, secondary brecciated zones and fractures within dolostone stockwork, but is also disseminated within the dark dolostones. Millimetre- to centimetre-sized crystals of amber, brown-red and black sphalerite occur. Locally, where porosity was high in the stockwork, geopetal sphalerite occurs with geopetal dolomite. Brecciation of the geopetal fill suggests repeated dissolution and filling of spaces in the stockwork. Galena as small cubes and rare 2 cm clots is less common within the showing. Pyrite also occurs locally. Mineralization on the Shorts Harbour showing consists of large crystals and masses of amber sphalerite and small crystals of sphalerite and galena distributed in the dolostones.

## River of Ponds Lake

A braided network of dolomite veins host minor sphalerite, galena and pyrite within eastward-dipping white-, rusty- and pink-weathering dolostones that replace Table Point limestones on the northwest shore of the lake (Grid Reference 4760 559545, NTS 12I/11). The veins, which form a 1- to 3-m-wide zone having a strike length of several metres, trend due north to northeast and dip steeply from 61 to 90° to the east. The galena forms streaks within fine fractures, and crystals and locally fist-sized clots within the veins. Crystalline black sphalerite is also present in the veins and was precipitated in spaces that were already lined by sparry dolomite.

An alteration zone of vuggy, pink- to rusty-weathering, white fine crystalline dolomite, locally enclosing rafts of white

limestone, borders the fracture zone. Although no visible mineralization exists in the pink dolostone, it reacted to the application of zinc-reactive solution suggesting it contains some secondary zinc minerals.

Ratios of lead isotopes in galenas from St. John Island and Rivers of Ponds Lake indicate they are highly radiogenic (Table 6).

# SUMMARY OF BASE-METAL MINERALIZATION IN THE MAP AREA

Three stratigraphic intervals in the Middle Cambrian to Middle Ordovician carbonate succession host minor mineralization.

Sphalerite and galena are hosted by the stromatolite member of the Late Cambrian Petit Jardin Formation. In the map area, this member consists of stromatolitic limestones and dolostones intercalated with oolitic limestones and dolostones, intraformational lime and dolomite conglomerates, parted limestones and thin-bedded dolostones. Although disseminated stratabound mineralization occurs at Pikes Feeder Pond, most of the galena, both at Pikes Feeder Pond and in drillholes near Forked Feeder Pond, is associated with later fracture systems. Sphalerite is a more important constituent of the Pikes Feeder Pond showing than previously reported. Both areas lie geographically close to areas where major faults intersect. Minor mineralization also occurs in the March Point Formation.

Stratabound dolomite breccias at the base of the Boat Harbour Formation contain a number of showings of iron pyrites and include minor sphalerite. Both showings lie adjacent to major northeast-trending fault zones.

Structurally controlled veins and bodies of epigenetic dolostones that replaced limestones low in the Table Point Formation bear galena and sphalerite. Bitumen in pore space and a pungent petroliferous odour is characteristic of the dolostone.

There is a sharp contrast between the isotopic lead from galena hosted by Cambrian and Middle Orodovician dolostones. The primitive lead of the Petit Jardin Formation may reflect a source within the underlying Precambrian basement. The strong preference of the galena for fracture spaces, and the close proximity of showings to major high-angle faults that are believed to intersect basement and perhaps have a history older than the Paleozoic, support this primitive source.

The highly radiogenic lead of the Table Point Formation suggests that there must have been some addition of radiogenic lead to the ordinary lead. This enrichment may have occurred as the mineralizing fluids passed up through the carbonate succession. An alternative and attractive idea is the derivation of the lead from a different source, in particular a shale or flysch basin, from which metal-bearing brines reached the host carbonates. The abundance of hydrocarbon residues in the porous Table Point dolomites lends support for this hypothesis. Indeed, it has been argued by many that there is a common genetic source for both hydrocarbons and base metals in carbonate rocks, namely brines derived from adjacent shale basins (Dozy, 1970; Anderson, 1978).

# INDUSTRIAL MINERALS

The Forteau Formation and the Hawke Bay Formation contain huge inventories of potash-rich shales and quartz-rich sandstones, respectively. Reserves of industrial-quality limestones in the area have already been reported by DeGrace (1974) but is discussed further in the text, along with dolomite resources of the area.

## Forteau Shales

The black to grey shales of the Forteau Formation are widespread throughout the map areas but are exposed best in roadstone quarries on Mount St. Margaret (NTS 12I/15). Analyses of the illitic shales of the Forteau Formation were first given by Smit (1971), and Swett and Smit (1972 a, b). They reported potash values from 4 to 10 percent over a thickness of approximately 24 m for shales in Labrador and suggested that these values were controlled by clay-sized, possibly authigenic potash feldspar. Smit (1971) also sampled the shale quarry at Mount St. Margaret (NTS 12I/15) and the shales from Frenchman's Gulch, Highlands of St. John (NTS 12I/14). The highest values at both sections were about 7 percent $K_2O$ but values at Mount St. Margaret drop as low as 1.5 percent $K_2O$ within the shale section. Recently, the Mount St. Margaret quarry was resampled by the Newfoundland Department of Mines and Energy (Dean and Meyer, 1984); analyses are given in Table 7. The samples confirm the average 7 percent $K_2O$ for the shales of the formation.

Such high $K_2O$ values suggest these shales would provide a suitable source of agricultural mineral additive, as suggested by Stevens and Knight (1974). (The people of the area have long realized the green thumb secret of these shales. They have planted their summer vegetables in the soils and decayed shale screes of the quarry area for many years.)

## Hawke Bay Quartz Arenites

White to pink quartz arenites of the Hawke Bay Formation are a prominent geological element of the Port Saunders and St. John Island map areas. The deepwater harbour of Hawkes Bay is neighbour to two areas of the formation each more than 4 km² in size, namely the south shore of Hawkes Bay near Otter Pond and the hilly country on the north side of Big East River. The formation is also found 7 km inland of Hawkes Bay at the southwest end of Western Brook Pond.

**Table 7.** Chemical analyses of major elements in shales from the Forteau Formation, Labrador Group, Three Mile Pond quarry, Mount St. Margaret (J. Meyer, unpublished data, 1984)

| Remarks | No. of Samples | % $SiO_2$ | $Al_2O_3$ | Total Iron as $Fe_2O_3$ | MgO | CaO | $Na_2O$ | $K_2O$ | $TiO_2$ | MnO | $P_2O_5$ | LOI |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Basal 20 m section of black to green-grey shales | 7 | 51.3 to 55.7 | 16.3 to 18.75 | 6.72 to 7.30 | 2.54 to 3.45 | 0.52 to 4.29 | 0.4 to 0.5 | 6.82 to 7.58 | 0.70 to 0.74 | 0.04 to 0.07 | 0.09 to 0.17 | 6.19 to 8.41 |
| Upper 10 m section of inter-bedded shales and limestones | 3 | 53.4 to 55.1 | 17.9 to 18.3 | 6.61 to 7.03 | 2.71 to 2.87 | 1.48 to 2.33 | 0.58 | 7.21 to 7.37 | 0.70 to 0.74 | 0.05 to 0.08 | 0.10 to 0.15 | 6.23 to 7.01 |

The arenites in these areas are gently dipping, massive, well-bedded deposits. Some beds of argillaceous sandstone and green-grey shale are distributed through the 150 m section of the formation. The quartz arenites contain $SiO_2$ from 92 to 98.6 percent, $Al_2O_3$ from 1.27 to 4 percent and $Fe_2O_3$ from 0.2 to 0.5 percent. (Butler and Greene, 1976; Newfoundland Department of Mines and Energy, Mineral Inventory Report, 121/11 Sia001 to Sia002).

The massive white to pink quartz arenites are composed of at least 95 percent quartz with some microcline and zircon. Hematite and limonite outline the original boundaries of the quartz sand grains that are now cemented by quartz overgrowths.

## Limestones

The Port Saunders map area contains enormous reserves of high-quality limestone. The limestones of the Table Point Formation underlie extensive areas of this map area close to the coast. The best grade limestone is rubbly weathering, thickly bedded, grey to dark grey (facies association 3 of the formation). It overlies a basal sequence up to 20 to 30 m thick of limestone and dolostone (associations 1 and 2) that is locally extensively dolomitized. The limestone resource forms east- to southeast-striking, gently south- to southwest-dipping outcrop belts that are bounded along their north and northeast edges by a series of scarps. Back Arm and Hawkes Bay provide deepwater harbours close to these resource areas and a bustling labour force is present in several towns along the coast in the Port Saunders map area. Limestone outcropping on Pointe Riche is now protected within the confines of a Parks Canada Historic Reserve.

Limestone resources in the map area were described by Harris (1962) and reiterated by DeGrace (1974) in his study of the limestone resources of Newfoundland and Labrador. The studies emphasized the limestone potential of the area, in particular of St. John Island where at least 650 million tons of high-grade Table Point Formation limestone underlies the western part of the island and 60 million tons occurs near St. John Harbour. Both reports were written at a time when all limestones in the area were assigned to the Table Head Group. However, they also published preliminary analyses of limestones from west of Eddies Cove West, which actually belong to the Catoche Formation. This is borne out by analyses of Table Point limestones from St. John Island (Figure 13, Table 8), which generally give 48.1 to 51.0 percent CaO, 0.2 to 3.0 percent MgO, 2.0 to 3.9 percent $SiO_2$ (with some samples up to 6.0 percent) and other impurities 0.4 to 2.5 percent (see Table 8). Catoche Formation limestones from west of Eddies Cove West contain 46 percent CaO, 5 percent MgO and 6 percent impurities reflecting the prominence of dolomitic burrow-mottles and thin seams in the limestone. High MgO values (up to 15 to 19 percent) in the northeast and west of St. John Island, reflect epigenetic dolomitization of the Table Point Formation limestone. This is especially common in the lower part of the formation in the northeast of the island and throughout the map area, e.g., east of Back Arm, and north and south of River of Ponds. Silica values probably reflect fine quartz silt and clay that occur along shaley seams or stylolites. Very high values (up to 9 percent $SiO_2$) will correspond to nodular chert horizons in the formation; they are, however, rare.

Although the St. John Island deposit is very large, has an excellent near shore location and no vegetation or gravel overburden, it is remote and inaccessible to a nearby labour force. However, similar Table Point limestones outcrop in an extensive belt east and southeast of Port au Choix and Gargamelle and in the area south of Spirity Cove (Figure 13). Drillholes in the Port au Choix area (Lopej and Edwards, 1976; Dickie and Lyn, 1979) indicate that there is at least 20 m of Table Point Formation along the north and northeast edge of its outcrop belt in this area. The maximum thickness

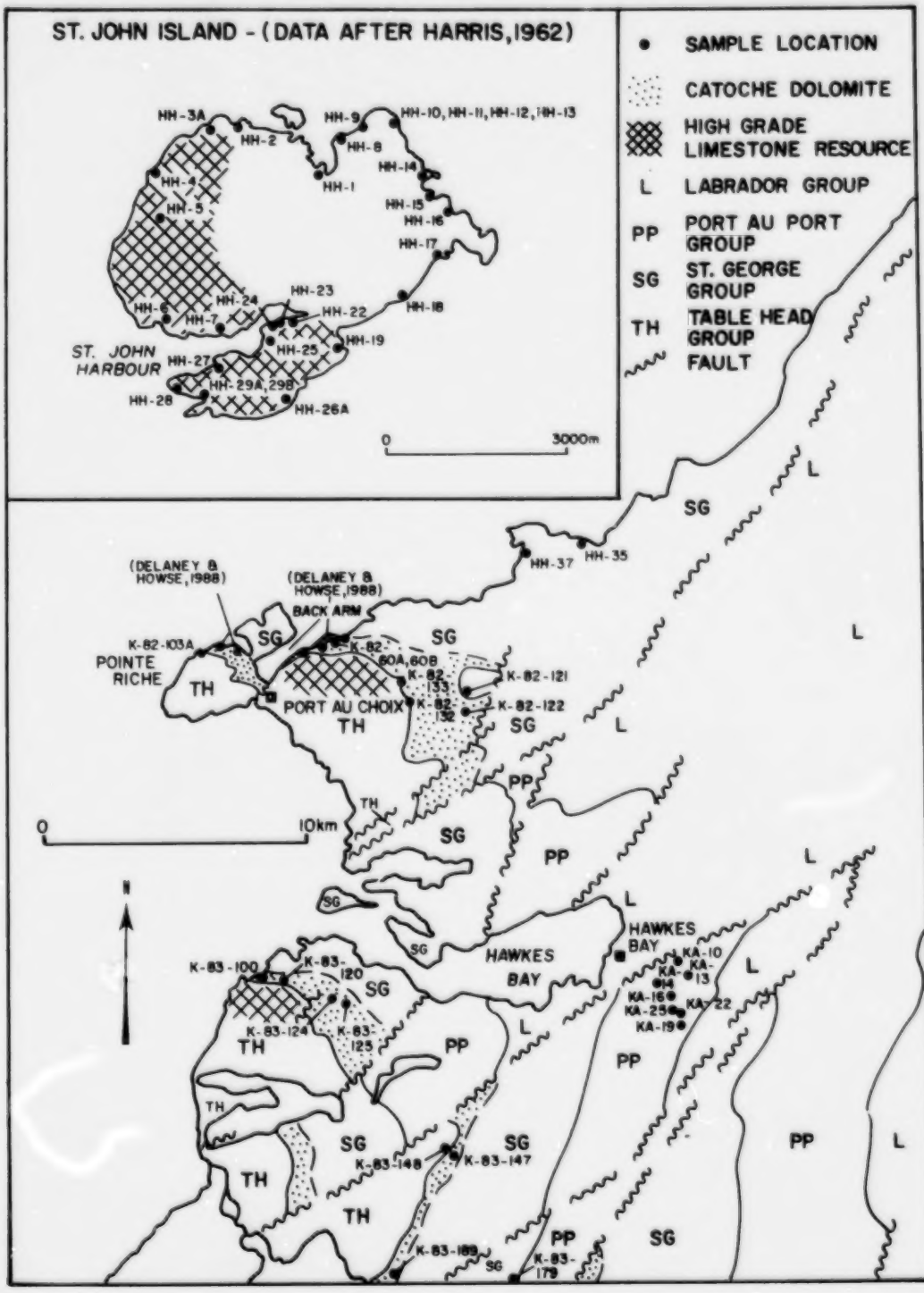



**Figure 13.** *Location map of dolomite sample sites and of major limestone and dolomite prospects, Port Saunders map sheet, and St. John Island.*

**Table 8.** Chemical analysis of limestones of the Table Point Formation on St. John Island; data from Harris (1962). Samples from the west side of island and from south of St. John Harbour are arranged in stratigraphic order through vertical sections 32 m and 36 m thick, respectively. Samples HH-3A-62L and HH-26A-62L represent the base of each section. Other samples from miscellaneous sites on the island are also listed

| Sample Number | Thickness (m) | CaO | MgO | $SiO_2$ | Other |
|---|---|---|---|---|---|
| St. John Island, West Side | | | | | |
| HH-3A-62L | 6.6 | 50.9 | 2.0 | 3.9 | 0.5 |
| HH-1/2-62L | 5.0 | 48.1-51.8 | 1.5-3.0 | 3.1-6.0 | 0.4-0.5 |
| HH-4-62L | 2.7 | 51.0 | 1.2 | 3.6 | 0.6 |
| HH-6-62L | 7.6 | 51.2 | 1.4 | 3.2 | 1.0 |
| HH-7-62L | 8.1 | 51.8 | 0.6 | 2.9 | 0.8 |
| HH-36-62L | 6.0 | | | | |
| St. John Harbour Area | | | | | |
| HH-26A-62L | 6.9 | 47.2 | 0.3 | 4.9 | 4.6 |
| HH-27/39A /31-62L | 6.6 | 47.9-48.8 | 1.9-4.2 | 2.8-5.1 | 2.0-2.2 |
| HH-24/29B-62L | 7.5 | 49.2-49.4 | 3.0-3.4 | 2.8-4.0 | 1.3-1.6 |
| HH-23-62L | 5.4 | 53.0 | 0.2 | 2.3 | 1.1 |
| HH-22-62L | 5.7 | 48.6 | 1.3 | 2.5 | 2.4 |
| Miscellaneous Locations | | | | | |
| HH-8-62L | 6.0 | 30.5 | 19.5 | 1.6 | 0.8 |
| HH-9-62L | 5.4 | 29.9 | 19.3 | 1.6 | 0.8 |
| HH-10-62L | 3.0 | 49.7 | 3.9 | 1.0 | 1.4 |
| HH-11-62L | 0.45 | 45.5 | 7.1 | 2.3 | 1.4 |
| HH-12-62L | 2.4 | 47.8 | 4.3 | 0.8 | 1.4 |
| HH-13-62L | 6.0 | 35.9 | 15.8 | 1.9 | 0.4 |
| HH-14-62L | 9.0 | 48.5 | 3.5 | 0.7 | 1.6 |
| HH-15-62L | 4.5 | 41.3 | 4.1 | 9.6 | 0.3 |
| HH-16-62L | 4.5 | 48.6 | 3.6 | 2.5 | 0.2 |
| HH-17-62L | 2.0 | 50.0 | 2.1 | 2.4 | 1.9 |
| HH-18-62L | 2.4 | 49.8 | 1.5 | 2.8 | 1.9 |
| HH-19-62L | 4.0 | 48.5 | 2.4 | 1.9 | 3.3 |
| HH-20A-62L | 2.5 | 43.5 | 4.2 | 6.2 | 4.5 |
| HH-20B-62L | 4.0 | 50.8 | 1.3 | 2.0 | 1.1 |
| HH-20C-62L | 4.5 | 52.0 | 1.3 | 2.0 | 2.1 |
| HH-20D-62L | 3.3 | 51.6 | 2.4 | 2.0 | 1.2 |

of the limestone in a downdip direction is closer to 60 to 100 m. An area at least 12 km² in size is underlain by the Table Point Formation and is covered by minor vegetation and sediment overburden. The potential minimum tonnage in this area (allowing for only 20 m of limestone) is 660 million metric tons. Immediately east of Back Arm, a minimum reserve of at least 275 million metric tons lies beneath a 30 to 75 m ridge. In the Spirity Cove area 2 km from the shore, Table Point Formation limestone underlies an elevated area (up to 60 m high) with a northfacing scarp. This area contains a potential minimum tonnage of 300 million metric tons. No geochemical analyses are available for either area but geological mapping indicates that the limestones are very similar to those on St. John Island and are expected to maintain the same grade. Caution is necessary in the areas described here because the basal 20 m of the formation is extensively dolomitized east of Back Arm and locally near Spirity Cove. The dolomitization front is, however, sharp and hence the dark-grey limestones of the Table Point Formation are generally unaffected.

## Dolomites

Dolomites with 3 percent impurities occur in the top of the Catoche Formation in the Port Saunders map area. The resource outcrops in two belts east of Back Arm and Spirity

**Table 9.** Chemical analyses of dolostones from the Catoche Formation, Port Saunders map area. Systematic sampling up through the dolomite section at Back Arm and Pointe Riche is provided by Delaney and Howse (unpublished data, 1989)

| Sample No. | $SiO_2$ | $Al_2O_3$ | Total Fe | MgO | CaO | $Na_2O$ | $K_2O$ | MnO | L.O.I. |
|---|---|---|---|---|---|---|---|---|---|
| Bustard Cove | | | | | | | | | |
| K-82-60A | 0.27 | 0.11 | 0.12 | 21.51 | 30.20 | 0.04 | 0.05 | 0.02 | 47.20 |
| K-82-60B | 0.71 | 0.19 | 0.14 | 21.61 | 30.03 | 0.05 | 0.09 | 0.02 | 46.88 |
| K-82-122 | 1.01 | 0.24 | 0.14 | 21.50 | 29.31 | 0.03 | 0.14 | 0.02 | 46.58 |
| Back Arm (Delaney and Howse, unpublished data) | | | | | | | | | |
| 9269 | 0.30 | 0.12 | 0.13 | 21.86 | 30.37 | 0.04 | 0.06 | 0.02 | 47.52 |
| 9271 | 0.57 | 0.19 | 0.14 | 21.71 | 30.06 | 0.03 | 0.08 | 0.02 | 47.24 |
| 9272 | 0.81 | 0.31 | 0.21 | 21.12 | 29.67 | 0.05 | 0.13 | 0.02 | 47.25 |
| 9273 | 0.91 | 0.19 | 0.13 | 21.52 | 29.95 | 0.04 | 0.09 | 0.01 | 46.93 |
| 9274 | 0.38 | 0.09 | 0.15 | 21.72 | 30.19 | 0.03 | 0.05 | 0.02 | 47.32 |
| 9275 | 0.62 | 0.13 | 0.12 | 21.57 | 29.83 | 0.03 | 0.07 | 0.01 | 47.21 |
| 9276 | 0.39 | 0.11 | 0.13 | 21.64 | 30.08 | 0.04 | 0.05 | 0.02 | 47.38 |
| 9277 | 3.41 | 0.24 | 0.17 | 20.95 | 29.20 | 0.04 | 0.11 | 0.02 | 45.71 |
| Pointe Riche (Delaney and Howse, unpublished data) | | | | | | | | | |
| 9178 | 0.74 | 0.29 | 0.16 | 21.51 | 29.83 | 0.04 | 0.14 | 0.02 | 47.20 |
| 9179 | 0.67 | 0.18 | 0.15 | 21.62 | 29.70 | 0.04 | 0.09 | 0.02 | 47.13 |
| 9181 | 1.49 | 0.43 | 0.22 | 21.16 | 29.76 | 0.04 | 0.21 | 0.02 | 46.65 |
| 9182 | 1.00 | 0.39 | 0.21 | 21.47 | 29.83 | 0.04 | 0.16 | 0.02 | 49.96 |
| 9183 | 0.90 | 0.33 | 0.24 | 21.60 | 29.80 | 0.04 | 0.16 | 0.02 | 47.02 |
| 9184 | 0.90 | 0.38 | 0.20 | 21.27 | 29.90 | 0.05 | 0.14 | 0.02 | 46.90 |
| 9185 | 0.39 | 0.13 | 0.20 | 21.45 | 29.68 | 0.04 | 0.05 | 0.02 | 47.60 |
| 9186 | 0.94 | 0.25 | 0.22 | 21.51 | 29.78 | 0.03 | 0.09 | 0.02 | 47.01 |
| Spirity Cove | | | | | | | | | |
| K-83-100 | 2.45 | 0.64 | 0.44 | 20.65 | 29.63 | 0.05 | 0.42 | 0.03 | 45.54 |
| K-82-120 | 4.45 | 0.20 | 0.14 | 20.29 | 28.40 | 0.03 | 0.08 | 0.02 | 44.76 |
| K-83-124 | 0.94 | 0.12 | 0.20 | 21.05 | 30.15 | 0.04 | 0.05 | 0.03 | 46.74 |
| K-83-125A | 1.61 | 0.49 | 0.20 | 20.64 | 29.88 | 0.04 | 0.21 | 0.03 | 46.34 |
| Miscellaneous Locations | | | | | | | | | |
| K-83-147 | 2.14 | 0.48 | 0.25 | 20.60 | 28.79 | 0.04 | 0.31 | 0.02 | 45.96 |
| K-83-189A | 0.33 | 0.07 | 0.14 | 20.72 | 30.00 | 0.04 | 0.03 | 0.03 | 47.15 |
| K-83-189 | 1.06 | 0.15 | 0.17 | 21.52 | 29.82 | 0.03 | 0.05 | 0.03 | 46.82 |

Cove. The dolomites are massive, tan grey, fine to medium crystalline, variably bituminous, and thick bedded. Nodular chert horizons occur locally. The dolomites replace the upper 40 to 60 m of the Catoche Formation although drillholes east of Back Arm (Lopej and Edwards, 1976; Dickie and Lyn, 1979) indicate that this thickness reaches at least 80 m locally. Like the stratigraphically younger limestone deposits of the Table Point Formation in the same areas, the dolomites strike east to southeast and dip gently (4 to 8°) to the south. Random samples analyzed from the area are shown in Table 9. Also included are analyses from two stratigraphic sections collected at Pointe Riche and Back Arm (Howse and Delaney, unpublished data, 1989). These analyses are part of an unpublished regional dolomite study that was briefly described by Delaney and Howse (1988). The analyses show that the dolomites contain 20 to 22 percent MgO, generally less than 1 percent $SiO_2$ but locally up to 4.5 percent and other impurities of less than 1 percent. Thin layers of white chalcedony and black chert account for rare high $SiO_2$ values. All the area lies within a few kilometres of deepwater harbours at Back Arm and Hawkes Bay and a large trained labour force exists in the immediate area. Good dolomite sections outcropping on the north side of the Pointe Riche Peninsula are protected from development within the Parks Canada Historic site.

**Table 10.** Chemical analyses of dolostones, Petit Jardin, Watts Bight and Table Point formations, Port Saunders map area

| Sample No. | $SiO_2$ | $Al_2O_3$ | Total Fe | MgO | CaO | $Na_2O$ | $K_2O$ | MnO | L.O.I. |
|---|---|---|---|---|---|---|---|---|---|
| Petit Jardin Formation | | | | | | | | | |
| K-83-23 1 | 11.60 | 2.00 | 0.63 | 18.00 | 26.00 | 0.04 | 1.48 | 0.02 | 39.77 |
| KA-83-10A | 1.62 | 0.23 | 0.30 | 20.83 | 29.04 | 0.04 | 0.14 | 0.02 | 46.29 |
| KA-83-13 | 8.55 | 2.69 | 0.77 | 6.90 | 39.36 | 0.04 | 1.67 | 0.02 | 38.89 |
| KA-83-14B | 5.35 | 1.04 | 0.48 | 20.07 | 27.99 | 0.05 | 0.66 | 0.04 | 43.81 |
| KA-83-16B | 1.41 | 0.40 | 0.32 | 21.07 | 29.54 | 0.04 | 0.24 | 0.06 | 45.93 |
| KA-83-17A | 3.74 | 0.41 | 0.47 | 20.57 | 28.62 | 0.03 | 0.26 | 0.06 | 45.. |
| KA-83-19A | 27.65 | 4.20 | 1.05 | 13.33 | 19.51 | 0.07 | 3.45 | 0.05 | 29.97 |
| KA-83-22 | 10.85 | 2.94 | 1.41 | 17.49 | 24.06 | 0.05 | 2.14 | 0.06 | 39.19 |
| KA-83-23 | 1.63 | 0.37 | 0.45 | 20.69 | 28.87 | 0.04 | 0.23 | 0.06 | 46.40 |
| Watts Bight Formation | | | | | | | | | |
| K-83-179 | 1.22 | 0.19 | 0.20 | 21.14 | 29.12 | 0.03 | 0.11 | 0.03 | 46.58 |
| Table Point Formation | | | | | | | | | |
| K-82-103A | 1.19 | 0.34 | 0.34 | 21.55 | 29.35 | 0.04 | 1.70 | 0.03 | 46.69 |
| K-82-121 | 1.34 | 0.23 | 0.18 | 21.66 | 29.23 | 0.03 | 0.12 | 0.03 | 46.38 |
| K-82-132A | 0.32 | 0.12 | 0.16 | 21.26 | 29.95 | 0.04 | 0.06 | 0.03 | 47.12 |
| K-82-132C | 0.23 | 0.06 | 0.15 | 21.38 | 30.04 | 0.03 | 0.03 | 0.03 | 47.05 |
| K-82-133A | 0.69 | 0.17 | 0.17 | 21.67 | 29.90 | 0.03 | 0.08 | 0.03 | 46.84 |
| K-83-148 | 0.56 | 0.17 | 0.15 | 20.92 | 30.57 | 0.04 | 0.05 | 0.03 | 47.18 |

East of Back Arm, the dolomite outcrops in an east-trending belt 5 km long by 0.5 to 1 km wide that then widens to 2 km as it turns south for 3.5 km in the area south of Bustard Cove. The belt underlies a low terrace between 15 and 30 m above sea level that is covered by shallow peat bogs and stunted evergreen brush. A scarp marks the northern edge of the outcrop belt. Reserves within the area immediately east of Back Arm are approximately 290 million metric tons based upon a 40 m stratigraphic interval. An additional 820 million metric tons underlie the more easterly area south of Bustard Cove.

The second area east of Spirity Cove, is an eastward-broadening belt 0.5 to 2.0 km wide and 4.5 km long, that underlies a northfacing hillside and terrace between 15 and 45 m high (locally reaching 60 m, north of Little Brook Pond). Reserves in this area approach 812 million metric tons.

Dolomites from other parts of the carbonate succession, although widespread, are considered less attractive for industrial use because of $SiO_2$ contained in the various rock types. Chert is a very common constituent of the tan-grey, crystalline dolomites of the Watts Bight Formation. Visible silica is not common in microcrystalline, light-grey dolostones of the Petit Jardin Formation but detrital quartz, silt, authigenic feldspars and fine clays can elevate silica values to as much as 27 percent (Table 10).

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*Note: Geological Survey Branch file numbers are included in square brackets.*

# APPENDIX 1

# Description of Measured Stratigraphic Sections

## SECTION 1

### HAWKE BAY FORMATION: South Shore Hawkes Bay

The section begins on the point 0.5 km west of the town of Hawkes Bay, and continues westward for approximately 4 km to a stream discharging onto the shore, 1.2 km east of Ourson Point. The section consists of a low rocky outcrop and cliff having covered intervals beneath muddy coves. A covered interval, 4.4 m thick, at the top of the section likely conceals shales, thin sandstones, and carbonates of the overlying March Point Formation. The top of the exposed quartz–arenite bed is believed to be the upper contact.

| Unit | Description | Unit Thickness m | Cumulative Thickness m |
|---|---|---|---|
| 18 | Quartz arenite: brown weathering, white and locally pink, fine grained associated with coarse-grained lenses, rare bioturbation, trough cross-stratification, 5- to 15-cm-thick sets, locally associated with ripple marks, some planar stratification having parting lineation; 50 cm covered interval 1.3 m from top; bed beneath covered interval has hummocky top due to soft sediment deformation | 6.26 | 151.15 |
| 17 | Sandstone: pink to locally reddish, with green spotting locally, 5- to 7-cm-thin stratification, syneresis cracks ?, numerous U-shaped and tubular burrows, *Cruziana* trails found on loose blocks, some small trough cross-sets 10 cm wide, 2 cm thick, mud pellets on base of some beds | 0.56 | 144.89 |
| 16 | Covered interval | 19.00 | 144.33 |
| 15 | Quartz arenite: pink to brown weathering, white, red and pink, coarse to fine grained, trough cross-stratified, some long and straight, others short and scoop-shaped, shale in abandoned scours, some planar cross-sets, straight and sinuous ripple marks common, 15- to 20-cm-thick planar stratification associated with parting lineation locally, some with heavy-mineral lamination, coarse sandstones may contain well-rounded, 0.2 to 0.5 cm, quartz pebbles and red mudclasts; some thin-covered intervals near base | 20.25 | 125.33 |
| 14 | Mostly covered: 48-cm-thick bed of yellow-weathering, white, fine grained, quartz arenite in the middle | 2.75 | 105.08 |
| 13 | Quartz arenite: white to pink with red spots, fine to medium grained, trough cross-stratified, (long, narrow, cylindrical troughs and short, broad scoop-shaped troughs) some planar cross-stratification, some ripple marks, locally pebbly | 3.00 | 102.33 |
| 12 | Mostly covered, quartz-arenite beds traced tentatively over a broad anticlinal and synclinal warp, 1.50 m unit of pink and white, trough crossbedded quartz arenite at base | 2.7 | 99.33 |
| 11 | Sandstone-shale: grey, bioturbated, very fine-grained sandstone, laminated, black phosphatic and shaly intraclasts, interbedded with grey and black, shaly siltstone and very fine-grained, sandstone, micaceous, retaining lamination although highly bioturbated, some U-shaped burrows, thin intraclastic conglomerates locally, basal 67 cm is covered | 1.95 | 96.63 |
| 10 | Sandstone: white-grey, very fine grained, 1 cm stratification, heavily bioturbated, some shale partings; lower 1.35 m is broken outcrops but contains similiar rocks. Sandstone is crosslaminated with abundant black phosphatic intraclasts | 1.88 | 94.68 |

| Unit | Description | Unit Thickness m | Cumulative Thickness m |
|---|---|---|---|
| 9 | Covered interval: white, well-sorted, fine-grained quartz arenite at top | 5.00 | 92.80 |
| 8 | Quartz arenite: white, very fine to medium grained, trough crossbeds, large and small planar cross-stratification, largest tabular sets are 40 cm thick having gently curved avalanche face 7 m wide, grit to medium-grained foresets, some ripple marks and planar lamination having parting lineation; locally red sandstone, some quartz pebbles; some poor exposure near top; lower intervals gently folded for 120 m along the foreshore | 17.00 | 87.80 |
| 7 | Covered interval | 3.00 | 70.80 |
| 6 | Quartz arenite and argillaceous sandstone: 1.56 m of greenish to brown weathering, white to pink quartz arenite, well sorted, fine grained, having some coarse to very coarse lenses, small planar and trough cross-stratification associated with straight and sinuous ripple marks, sand volcano with mud filled pit, U-shaped burrows locally; overlying 64 cm of highly bioturbated, muddy slightly micaceous, grey sandstone, phosphatic grains | 2.20 | 67.80 |
| 5 | Quartz arenite (Cible Point): white, red toward base, fine grained, cross-stratification, includes some large planar crossbeds, crossbedded pebbly grit layer 35 cm from top, foresets graded, pebbles 0.5 to 0.75 m in diameter, white quartz; pebbles in small pockets on bedding planes low in the unit, maximum size 4 cm, angular to rounded, white quartz, red granite, red sandstone and shale intraclasts. Basal quartz arenite contains glauconite where interlayered with red sandstones | 10.50 | 65.60 |
| 4 | Sandstone and shale: 1.6 m of thinly stratified red, very fine-grained, micaceous and quartzose sandstone rich in worm burrows, trails, *Cruziana*, *Ruzophycus* scratch marks, *Skolithus* and simple and complex U-shaped burrows, internally laminated with some crosslamination and small crossbeds, straight ripple marks, parting lineations, red shale partings and thin beds, (some sandstone blocks show sand-filled cracks), shale interbeds increase downwards; these beds overlie 2.50 cm of grey-white, very fine- to fine-grained quartz arenite and micaceous sandstone that are laminated and thinly bedded with some crosslamination; linguoid ripple marks, U-shaped and simple burrows, glauconite, grey shale parting; red shaly bioturbated, micaceous sandstone, 36 cm thick, 85 cm above base | 4.10 | 55.10 |
| 3 | Covered interval to Otter Pond Brook | 11.00 | 51.00 |
| 2 | Shale and thin sandstone: grey-green and green shale and 10 cm interbeds of green, very fine-grained calcareous sandstone, flat, fluted and scour bases, some carrying scratch marks, some worm trails, plug-shaped burrows; tops of beds are flat with rare ripple marks; some sandstone is unsorted, pebbly medium to very coarse grained; sandstone dykes 3 to 5 cm thick, cut acros the shales, trends 055, 097 and 144°; fossiliferous-hyolithids, brachiopod fragments and trilobites including *Olenellus fremonti* Howell. Approximately 9 m of covered section below the shales | 20.00 | 40.00 |
| 1 | Quartz arenite: poorly exposed, white, crossbedded, white quartz arenite. | 20.00 | 20.00 |

Rests upon rusty-weathering, grey bioturbated and fossiliferous sandstone and grey shale of the top of the Forteau Formation. A 4.5-m-thick, black fossiliferous, oncolitic, oolitic grainstone occurs 13.5 m below the Hawke Bay/Forteau Formation boundary. Total Forteau Formation exposed in the section is 18.5 m





# SECTION 2

## HAWKE BAY–MARCH POINT FORMATIONS: North Shore of Hawkes Bay

The section is located 1 km west of Great Point along a rocky shoreline, strata younging to east.

MARCH POINT FORMATION (incomplete)

| Unit | Description | Unit Thickness m | Cumulative Thickness m |
|---|---|---|---|
| 4 | Dolostone: yellow to rusty weathering, dark grey, fine grained, burrowed, uneven thin stratification, some crosslamination with some thin layers and lenses of intraclastic grainstone and rudstone; dykes of dolarenite cut the dolostones near the top | 9.00 | 22.90 |
| 3 | Dolostone and dolrudite: 10 to 60 cm beds of scour-based intraformational dolrudite, discoid clasts locally edgewise, intercalated in burrowed, thinly stratified dolostone, some crosslamination, local convolution | 1.95 | 13.90 |
| 2 | Dolostone: rusty- to yellow-weathering, thinly stratified, bioturbated, dark-grey dolostone, some lenses of dolarenite inarticulate brachiopod, shaly drapes, vugs, small lenses of intraformational dolrudite in lower 60 cm, small cryptalgal mounds 70 cm from top | 8.70 | 11.95 |
| 1 | Shale–dolomitic sandstone: dark-grey to black, micaceous shale with 0.5 to 1.0 cm beds of rippled, and bioturbated sandstone and siltstone at base, and burrowed, laminated, and flaser-bedded, very fine-grained sandstone and shale in the upper 90 cm, inarticulate brachiopods throughout; conformable contact | 3.25 | 3.25 |

HAWKE BAY FORMATION (incomplete)

| | | | |
|---|---|---|---|
| 3 | Quartz arenite: white, fine grained, trough cross-stratified, 25 to 30 cm sets, top is deformed by soft sediment deformation | 14.8 | 43.35 |
| 2 | Sandstone–shale: Beds, 30 to 100 cm thick, of very fine- to fine-grained quartz arenite and argillaceous sandstone, abundant bioturbation including simple and spreite-filled U-shaped burrows and tubular burrows filled by mud and sand, planar lamination and thin stratification, some cross-stratification, some ripple marks, shale intraclasts in sandstone, some beds with intercalated shale and thin sandstone, triple pointed mudcracks at base of thin sandstone, back-filled tubular burrows with good spreite, rhomboid ripple marks | 5.85 | 28.55 |
| 1 | Quartz arenite: pink and white, fine to medium grained, trough crossbedding having shallow scours, some planar crossbeds, some shale intraclasts, covered base | 22.70 | 22.70 |

# SECTION 3

## MARCH POINT FORMATION–PETIT JARDIN FORMATION: South Shore of Hawkes Bay

The section begins 1.2 km east of Ourson Point (Port Saunders map sheet) and continues through gently dipping strata to the west side of the point. Low rocky, often broken, outcrops above a sandy and muddy shoreline typify the section.

PETIT JARDIN FORMATION (incomplete)

| Unit | Description | Unit Thickness m | Cumulative Thickness m |
|---|---|---|---|
| | Middle stromatolite member (incomplete) | | |
| 26 | Intraformational dolrudite: 20 to 40 cm beds of edgewise breccia with 1- to 10-cm-long discoid dolostone clasts in mud matrix; disintegrated into blocks | 0.60 | 47.56 |
| 25 | Argillaceous dololaminate and interlayered dolorudite, skeletal grainstone and dolomitic parted limestone: lamination and mudcracks in fine beds, edgewise discoid clasts in breccias | 0.90 | 46.96 |
| 24 | Lime rudstone: intraformational discoid clasts in stellate edgewise clusters locally, large inarticulate brachiopod *Dicellomus*, and trilobite fragments (*Arapahoia* and *Blountia*) set in a dolomitic lime mudstone matrix | 0.45 | 46.06 |
| 23 | Dolomitic parted limestone, oolitic lime grainstone, bioturbated lime wackestone–mudstone and dololaminite: parted limestone and wackestone is unevenly thin bedded, locally disrupted by mudcracks and containing lenses of intraformational, bioclastic rudstone, cryptalgal-laminite, dolomite laminae and dolarenite; grainstone 12 cm thick, 1 m above base is crosslaminated; dololaminite contains mudcracks, fissure cracks and lenses of rudstone | 2.81 | 45.61 |
| 22 | Boundstone: dark-grey, dolostone and limestone laminae, low mounds, pockets of intraformational pavement, shale drapes with mudcracks | 0.23 | 42.80 |
| 21 | Dolostone: laminated with intraclastic layers and lenses, top 50 cm is covered. | 0.95 | 42.57 |
| 20 | Dolomitic lime boundstone: three beds, 23 to 45 cm thick, of nested mounds of LLH forming 60 cm diameter heads, poorly exposed, low stromatolite mounds composed of tightly packed LLH columns or 80 cm mounds surrounded by intraclastic breccia, and capped by 60 cm mounds of LLH and digitate growth forms | 1.43 | 41.62 |
| 19 | Covered interval | 1.36 | 40.19 |
| 18 | Dolomitic lime boundstone: stromatolite, 60 to 100 cm beds with large mounds of LLH and flat laminite in upper beds and a basal bed of mudcracked and fissure-cracked flat to wavy cryptalgal laminite | 2.48 | 38.83 |
| 17 | Dolarenite: intraclastic, quartz sand, scour base | 0.29 | 36.35 |
| 16 | Dololaminite: undulose to flat lamination with shaly partings, fissure cracks and mudcracks, layers of rip-up dolorudite | 0.80 | 36.06 |
| 15 | Covered interval | 1.08 | 35.26 |
| 14 | Boundstone: dolostone with large mounds with continuous lamination, reddened argillaceous caps, lower part is red and buff mottled; dolo-mudstone drapes between mounds | 0.50 | 34.18 |

| Unit | Description | Unit Thickness m | Cumulative Thickness m |
|---|---|---|---|
| 13 | Covered interval | 0.80 | 33.68 |
| 12 | Dolostone: wavy thinly stratified with mudcracks with nested, circular stromatolites and abundant vugs, some scours | 0.90 | 32.88 |
| 11 | Intraclastic dolrudite | 0.34 | 31.98 |
| 10 | Covered interval includes contact of Middle stromatolite and lower dolostone member | 7.90 | 31.64 |
| | Lower dolostone member | | |
| 9 | Dolostone: thinly stratified, mudcracks, small stromatolites, some dolarenite and intraclastic layers 3 to 5 cm thick, fenestrae common | 0.37 | 23.74 |
| 8 | Covered interval | 4.90 | 23.37 |
| 7 | Dolostone: laminated, mudcracked, shaly partings and thin beds | 0.42 | 18.47 |
| 6 | Covered interval | 1.85 | 18.05 |
| 5 | Dolostone, dolomitic mudstone and shale: red shale and shaly dolostone and buff-weathering, light-grey dolostone having shale partings or stylolites, unevenly thinly stratified, mudcrack polygons, small ripple marks, desiccation breccias, small cryptalgal structures, pans of cryptalgal dololaminite; massive, hackly weathering green-grey dolomitic mudstone near base, minor covered intervals | 3.30 | 16.20 |
| 4 | Covered interval | 3.00 | 9.90 |
| 3 | Boundstone dolostone: desiccated algal pans and mounds of LLH, some bioturbated dolostone with phosphatic grains in the burrows | 0.55 | 9.90 |
| 2 | Covered interval | 5.90 | 9.35 |
| 1 | Dolostone, shaly dolostone, shale and mudstone: red, green-grey and grey shale, with dolomitic laminae, mudcracks, intraclast layers, overlain by thin stratified and laminated, stylolitic fenestral-rich, mudcracked, ripple-marked dolostone, some with shale drapes, sequences up to 90 cm thick; red and green hackly weathering, massive mudstone at the base of some sequences | 3.45 | 3.45 |
| | MARCH POINT FORMATION | | |
| 18 | Cryptalgal dolostone: yellow-weathering, vuggy dolostone with mounds surrounded by desiccated dolostone, basal 20 cm poorly exposed | 0.73 | 28.47 |
| 17 | Shaly dolostone and dolostone: planar laminated with shale partings, mudcracked, some desiccation breccias | 0.61 | 27.74 |
| 16 | Boundstone–dolostone: stromatolite mounds built of LLH with a smooth lamination at rim of mounds, each mound is isolated by desiccated, laminated and thinly stratified dolostone with granular dolarenite in wide fissure cracks | 0.67 | 27.13 |
| 15 | Dolostone–mudstone: blue-grey, hackly weathering mudstone with dolostone lenses, inarticulate brachiopod fragments overlain by 35 cm of unevenly thinly bedded dolostone with a few trace fossils | 0.80 | 26.46 |

| Unit | Description | Unit Thickness m | Cumulative Thickness m |
|---|---|---|---|
| 14 | Covered interval | 1.33 | 25.66 |
| 13 | Dolostone: brown- to yellow-weathering, light-grey, wavy to planar-thin stratified, dolostone with mudcracks, ripple marks, wrinkle marks, tepee structures and some bioturbation in distinct layers, a scour based black dolarenite 25 cm thick, 1.45 cm above base; 22 cm covered interval at base | 2.13 | 24.33 |
| 12 | Boundstone: stromatolitic dolostone with broad mounds, upward expanding layers, with some LLH structure but the mounds are composed of crinkly lamination, 1 cm argillaceous zones separate each major growth layer | 1.20 | 22.20 |
| 11 | Dolostone–shale: thinly stratified and laminated, light-grey dolostones with mudcracked shale drapes, lenses of crosslamination and large tepee structure with associated brecciation intercalated with mudcracked grey shale with dolomite laminae | 1.70 | 21.00 |
| 10 | Covered interval with 28 cm of mudcracked grey shale plus dolomite laminae 55 cm above base | 1.30 | 19.30 |
| 9 | Dolostone: rusty- to orange-weathering, stylolitic, dark-grey to grey dolostone, unevenly thin-bedded, shaly drapes that are mudcracked, lenses and layers of intraformational dolorudite, 14 cm bed of granular intraclastic dolarenite 31 cm above base: hummocky top to unit suggests stromatolite mounds, fenestrae | 1.43 | 18.00 |
| 8 | Covered intervals with beds of rusty-yellow-weathering shaly dolostone, dolomitic shale, and dolostone, planar-thin bedding and lamination, mudcracks, small ripple marks, rare intraclastic granular dolarenite, some inarticulate brachiopods in burrowed shaly dolostone near top | 2.00 | 16.57 |
| 7 | Argillaceous dolostone: rusty-yellow-weathering, dark-grey to grey dolostone, uneven and wavy thin stratification and lamination, shale partings common, lenses of intraformational breccia, small ripple marks, possible rain pits, lenses of crosslamination, mudcracks and shrinkage cracks near top | 2.80 | 14.57 |
| 6 | Covered interval | 1.70 | 11.77 |
| 5 | Intraformational dolorudite: beds 6 and 10 cm thick seperated by 2 cm of wavy, bioturbated shaly dolostone, dolorudite composed of densely packed clasts, with rip-up clasts of rolled up laminae | 0.18 | 10.07 |
| 4 | Dolostone: poorly exposed shaly dolostone having 4-cm-thick, scour-based intraclastic rudstone at base | 0.54 | 9.89 |
| 3 | Covered interval with some bioturbated, wavy thin-bedded, argillaceous dolostone | 3.45 | 9.35 |
| 2 | Dolostone: buff to yellow-weathering, unevenly thin stratification, shale partings, bioturbated, with frequent lenses, layers and gradational patches of intraformational edgewise brecia having discoidal clasts up to 8 cm in length of laminated dolostone, gutter, casts, ripple marks | 1.50 | 5.90 |
| 1 | Covered interval: Strata overlies Hawke Bay sandstones; the interval probably contains shale and thin sandstone of the base of the March Point Formation | 4.40 | 4.40 |

# SECTION 4

## BOAT HARBOUR FORMATION–WATTS BIGHT FORMATION: Eddies Cove West

The section begins north of Fish Point and continues essentially uninterrupted along a low rocky shoreline of Old Man Cove to Hunters Point, west of Eddies Cove West; section is overlain by Catoche Formation (Section 8, page 122).

| Unit | Description | Unit Thickness m | Cumulative Thickness m |
|---|---|---|---|
| | Barbace Cove Member (Units 102 to 122) | | |
| 122 | Dolomitic, shaly lime mudstone: finely laminated, some ripple marks, lenses of ripup, discoid intraclasts and skeletal, fine-grained grainstone, mudcracks | 0.29 | 104.44 |
| 121 | Skeletal packstone–wackestone: crinoid and gastropod-rich layers and lenses, also ostracods, trilobites | 0.62 | 104.15 |
| 120 | Calcareous shale to shaly lime mudstone: undulose lamination, mudcracks | 1.16 | 103.53 |
| 119 | Packstone–wackestone: basal scour overlain by intraclastic lime conglomerate, skeletal-rich and intraclast-rich grainstone and packstone interlayered with bioturbated wackestone, less packstone upward, but some intraclastic layers, straight ripple marks, generally lenticular and wavy bedded, trilobites, brachiopods, high-spired and planispiral gastropods, cephalopods | 0.55 | 102.37 |
| 118 | Lime mudstone and dolostones: laminated and flaser bedded, mudcracked | 0.26 | 101.82 |
| 117 | Wackestone–packstone: scour base, bioturbated, skeletal packstones, small gastropods, irregular top | 0.22 | 101.56 |
| 116 | Lime mudstone: dolomitic upward, laminated and flaser bedded, mudcracks | 0.68 | 101.34 |
| 115 | Lime mudstone: wavy thin bedding, bioturbation, wrinkle and ripple marks, pink calcite and fluorite in vugs | 0.92 | 100.66 |
| 114 | Grainstone: scour base, large sinuous ripple marks on top, internally crossbedded, rich in intraclasts, skeletal grains and possibly ooliths, ripple marks planed off locally, lime mudstone drapes in troughs and on crests | 0.11 | 99.74 |
| 113 | Lime mudstone–wackestone: well bedded, bioturbated; skeletal grains including trilobites and gastropods | 0.56 | 99.63 |
| 112 | Grainstone: skeletal and intraclastic, rippled top, lenses out along strike | 0.12 | 99.07 |
| 111 | Wackestone–packstone: thinly bedded, layers of skeletal packstone strongly bioturbated in some layers, trilobites, brachiopods common | 1.96 | 98.95 |
| 110 | Packstone–grainstone layers (24 to 30 cm) interbedded with bioturbated wackestone layers (19 to 26 cm): grainstone–crossbedded, scour-based, intraclasts and skeletal grains, straight large ripple marks common; wackestone is thinly bedded with some flaser bedding, shale drapes, vugs containing fluorite | 1.17 | 96.99 |
| 109 | Packstone–grainstone: skeletal grains, intraclasts and coated grains, rich in trilobites: sinuous ripple marks | 0.32 | 95.82 |

| Unit | Description | Unit Thickness m | Cumulative Thickness m |
|---|---|---|---|
| 108 | Lime mudstone–dolostone: thin bedded, distinctive yellow-grey weathering, nodular, thickens to east | 0.34 | 95.50 |
| 107 | Packstone–grainstone: skeletal–intraclastic grains, gastropods, trilobites | 0.06 | 95.16 |
| 106 | Lime mudstone: flaser and lenticular bedded, dolostone layers, some grainstone | 0.62 | 95.10 |
| 105 | Lime mudstone and shale: thinly bedded and laminated, wrinkle marks and linear ridges, flaser bedding and shaley near base | 0.53 | 94.48 |
| 104 | Lime mudstone–dolostone: laminated, locally wavy lamination, mudcracks in lower 50 cm; dolostone has scattered, white, rounded to angular, vug-quartz pebbles and sand locally on lamination; locally covered | 1.28 | 93.95 |
| 103 | Dolostone–lime mudstone: burrow-mottled, light-grey, covered base | 0.20 | 92.67 |
| 102 | Covered interval: gravel beach and foreshore. (The contact between the lower member and the overlying Barbace Cove Member lies in this interval) | 3.87 to 11.85 | 92.47 |
| | Lower Member | | |
| 101 | Boundstone: black to light-grey, rubbly weathering, 50 cm beds of large mounds composed of basal cores of dark-grey thrombolite and white-colored cabbage-head stromatolite that is capped by smooth laminated light-grey stromatolite over the complete mound; an upper mound zone of black-laminated mounds and SH-V columnar stromatolite capped by mounds of aberrent conophyton-like structures and thrombolite-*Renalcis* structure, mounds are steep-sided and circular in shape, locally rich in gastropods and trilobites, vugs, chert nodules in top beds, locally dolomitized margins to mound; capped by finely laminated and flaser-bedded lime mudstone and dolostone with *Chondrites* and locally convolution | 1.40 | 80.62 |
| 100 | Wackestone: bioturbated, locally intense, gastropods; overlying thin-bedded dolomitic lime mudstone having bioturbated wackestone; sharp base to unit | 1.06 | 79.22 |
| 99 | Dolostone and lime mudstone: flaser and lenticular bedded, scours, some irregular 'solution' surfaces, some bioturbation, *Chondrites*, small cryptalgal mounds, chert nodules | 2.03 | 78.16 |
| 98 | Wackestone–boundstone: thinly bedded, bioturbated, quartz-lined vugs, some trilobites and gastropods, stylolites, surrounding very wide, flat-topped thrombolite mounds | 1.43 | 76.13 |
| 97 | Boundstone: rubbly weathering, clotted structure, *Renalcis;* bioturbated wackestone and skeletal-intraclastic packstone in intermound areas, some gastropod and trilobite, grains and skeletons enclosed in mounds | 1.22 | 74.70 |
| 96 | Stromatolitic boundstone: two beds of mounds composed of LLH structure with some digitate structure coring some mounds, flaser- and thin-bedded lime mudstone–dolostone in wide intermound areas, quartz-lined vugs | 0.79 | 73.48 |
| 95 | Lime mudstone–dolostone: irregular scour base, flaser and lenticular bedded, some layers of bioturbated lime mudstone associated with low stromatolite mounds, near base and top, lower mounds of LLH, upper of SH-C structure | 0.72 | 72.69 |
| 94 | Lime mudstone with dolostone layers: burrows, thinly bedded | 0.35 | 71.97 |

| Unit | Description | Unit Thickness m | Cumulative Thickness m |
|---|---|---|---|
| 93 | Lime mudstone–dolostone: flaser and lenticular bedding, lamination, some *Chondrites*, scours common, local convolution | 1.38 | 71.62 |
| 92 | Wackestone–lime mudstone: sharp base, well-bedded, bioturbated skeletal wackestone, gastropods, trilobites overlain by 13 cm of laminated dolostone having limestone lenses, some *Chondrites* | 0.67 | 70.24 |
| 91 | Lime mudstone–dolostone: flaser and lenticular bedded, local lenses of convoluted laminae, some bioturbation, quartz-lined vugs; isolated mounds at base, structure obscure | 1.50 | 69.57 |
| 90 | Wackestone: thin bedded, bioturbated | 0.52 | 68.07 |
| 89 | Lime mudstone: thin bedded and lenticular, shale drapes, trails, quartz-lined vugs | 0.24 | 67.55 |
| 88 | Boundstone: rubbly weathering, 50 cm diameter heads, 10 cm high, stromatolite, LLH–SH-C structure, irregular lobate pattern on top of mounds, stylolites, large quartz-lined vugs, mound trend approximately 020°, surrounded by thin-bedded lime mudstone–dolostone facies | 0.43 | 67.31 |
| 87 | Wackestone: associated with packstone layers and dolostone drapes, intensely bioturbated in basal 58 cm, smoother flaser bedding at top, longitudinal ridges | 0.85 | 66.88 |
| 86 | Lime mudstone: flaser and lenticular bedded, smooth beds, scours, spar-filled vugs | 0.90 | 66.03 |
| 85 | Wackestone–packstone: interlayered and some flaser-bedded lime mudstone layers, bioturbated, locally gastropod rich | 1.37 | 65.13 |
| 84 | Grainstone: intraclastic and skeletal, scour base, lime mudstone flaser, brachiopods, cephalopods and brachiopods | 0.10 | 63.76 |
| 83 | Lime mudstone with dolostone layers: lenticular and flaser bedded, minor bioturbation, some highly convoluted laminae, some sized-sorted gastropod lenses, mostly dolostone in the top 25 cm | 0.89 | 63.66 |
| 82 | Wackestone: well-bedded, bioturbated, small conical boundstone mounds, 5 to 7 cm diameter, 5 cm high, small, straight, anastomosing ripple marks, quartz-filled vugs; scour base locally overlain by intraclasts | 0.41 | 62.77 |
| 81 | Lime mudstone and minor dolostone layers and drapes: smooth, flat to wavy bedding giving way upward to flaser and lenticular bedding | 1.92 | 62.36 |
| 80 | Wackestone: bioturbated, sharp base | 0.80 | 60.44 |
| 79 | Covered interval: sandy beach. Unit 81 west of beach may be equivalent to bed 76 to the east | 0.25 | 59.64 |
| 78 | Wackestone–packstone capped by dolomitic lenticular wackestone: packstone lenses of skeletal debris including brachiopods, gastropods, eocrinoids and trilobites | 0.90 | 59.39 |
| 77 | Grainstone: intraclastic and skeletal, very coarse to coarse lime sand grains, poorly developed ripple marks on top, crosslaminated, gastropods, cephalopods, eocrinoids | 0.03 | 58.49 |
| 76 | Lime mudstone and dolostone: lenticular and flaser bedded, smooth to undulose bedding planes, laminated layers, locally deformed lamination associated with brecciation of laminae, small ripple marks, some scarce trails, lenses of intraclasts, layers of moderate bioturbation, quartz-lined vugs; basal 37 cm is dolomitized | 0.95 | 58.46 |

| Unit | Description | Unit Thickness m | Cumulative Thickness m |
|---|---|---|---|
| 75 | Wackestone: bioturbated, massive to thinly bedded, dolomitized in lower part | 1.00 | 57.51 |
| | Beds traced east of wharf at Eddies Cove West. Limestones are dolomitized to grey dolomites with sparry dolomite parallel to bedding. | | |
| 74 | Wackestone: dolomite, bioturbated | 0.66-1.00 | 56.51 |
| 73 | Lime mudstone–wackestone: dolomitic, undulose thin bedding | 0.42 | 55.51 |
| 72 | Wackestone and packstone having intraclastic grainstone lenses: bioturbated | 0.55 | 55.09 |
| 71 | Covered interval | 0.30 | 54.54 |
| 70 | Lime wackestone–mudstone: thinly bedded, bioturbation locally intense, dolomitic thin beds | 0.75 | 54.24 |
| 69 | Covered interval | 0.40 | 53.49 |
| 68 | Lime mudstone–wackestone: thin-bedded, laminated, dolostone drapes and layers, local scour and fill, intensely bioturbated in some layers, layers of size-sorted gastropods, laminated dolarenite layers | 1.65 | 53.09 |
| 67 | Lime mudstone and some wackestone: lenticular bedded, some fine to large bioturbation subparallel to bedding, mostly smooth bedding planes, dolostone laminae, some scours, gastropod-rich lenses, some mudflake conglomerate, possible gypsum-lath molds | 1.13 | 51.44 |
| 66 | Wackestone–lime mudstone: bedded, laminated dolostone layers, bioturbated, gastropods, rare trilobites, straight cephalopods, lenses of intraclastic calcirudite near top, small stromatolite mounds in bioturbated dolomitic wackestone developed locally at base of unit | 0.61 | 50.31 |
| 65 | Lime mudstone–dolostone: thin bedded and lenticular bedded, lamination, minor bioturbation | 0.32 | 49.70 |
| 64 | Stromatolitic boundstone: two beds of small mounds composed of columnar and laterally linked stromatolites, bedded, intraclastic packstone between mounds | 0.35 | 49.38 |
| 63 | Wackestone–packstone: wavy bedding at first replaced upward by bioturbated, massive bedding, some isolated boundstone mounds, intense bioturbation locally, gastropods | 1.45 | 49.03 |
| 62 | Lime mudstone having shaly lenses: smooth wavy, flaser and lenticular bedding, lamination, subhorizontal burrows, intraclastic calcirudite layers, convolution of laminae, broken top to bed, less bioturbation upward | 1.00 | 47.58 |
| 61 | Boundstone: black, rubbly weathering, thrombolite having some columnar structure overlain by stromatolite, rich in trilobites, brachiopods, gastropods and straight cephalopods 'conophyton-like' aberrant structures of laminar lime mudstone forms outer margin of mounds, intermound areas filled by bedded packstone and wackestone | 1.32 | 46.58 |
| 60 | Dolostone and lime mudstone: lenticular smooth bedding, lamination, lenses of lime intraclasts, more lime mudstone upward, some bioturbation, mudcracks near top of unit, fossils rare | 1.00 | 45.26 |
| 59 | Stromatolitic boundstone: coalesced mounds, composed of interlayered columnar and laminar structure, edgewise intraclastic conglomerate between heads | 0.68 | 44.26 |

| Unit | Description | Unit Thickness m | Cumulative Thickness m |
|---|---|---|---|
| 58 | Lime mudstone–wackestone: lenticular bedding, dolostone layers and drapes, *Skolithus*, bioturbation increasing upward, some skeletal intraclastic packstone, gastropods; some small stromatolitic mounds capped by bioturbated dolostone in basal 40 cm; sharp scour above | 1.43 | 43.58 |
| 57 | Boundstone: scour base overlain by 10 cm of intraclastic grainstone overlain by thrombolitic mounds, 33 cm high, with stromatolitic structure | 0.18-0.41 | 42.15 |
| 56 | Lime mudstone and dolostone: smooth wavy, lenticular to flat thin bedding, some convoluted laminae, some slightly to intensely bioturbated layers, dolostone predominates near base | 1.13 | 41.74 |
| 55 | Lime mudstone: highly bioturbated | 0.15 | 40.61 |
| 54 | Lime mudstone–dolostone: wavy, lenticular and flaser bedded, internally laminated and crosslaminated, ripped up and convoluted lamination, trails, mudcracks near top | 1.17 | 40.46 |
| 53 | Lime mudstone–wackestone: well bedded, bioturbated, scours, stylolites, large gastropods and straight cephalopods, some boundstone mounds near base, locally laminated | 0.89 | 39.29 |
| 52 | Covered interval | 0.20 | 38.40 |
| 51 | Lime mudstone: thin bedded, lenticular bedded, lamination, minor bioturbation, lenses of intraclastic packstone, convoluted lamination in lenses, some dolostone layers | 0.48 | 38.20 |
| 50 | Covered interval | 0.20 | 37.72 |
| 49 | Wackestone, parted lime mudstone and parted dolostone: bioturbated beds within smooth flat to irregular thin bedding and lenticular bedding, scours, lamination, lenses of highly convoluted laminae, dolostone in basal 35 cm overlain gradationally by parted limestone | 0.78 | 37.52 |
| 48 | Covered interval | 0.34 | 36.74 |
| 47 | Dolostone: smooth to undulose, thin bedding and lenticular bedding, lamination, some deformation, some bioturbation, fine wrinkle marks, possible mudcracks near top of bed where it hosts chert nodules and abundant vugs filled with white and yellow calcite and dolomite spar as well as white quartz and purple fluorite | 0.97 | 36.40 |
| 46 | Boundstone: black, large, spherical, isolated to coalesced, oriented mounds, intraclastic base beneath digitate stromatolitic core surrounded by outer zone of *Renalcis* and thrombolite, abundant gastropods and some cephalopods trapped in mounds, intermound fill is gastropod-rich, skeletal and intraclastic grainstone, trilobites, straight cephalopods, some bioturbation; this chert makes stromatolite–thrombolite contact | 0.97-1.09 | 35.43 |
| 45 | Lime wackestone: dolomitized thinly bedded, lamination, burrows and trails | 0.58 | 34.34 |
| 44 | Oolitic grainstone: laminated dolostone layers and drapes, intraclastic grainstone layers occur, scours, laminated dolostone layers show disruption of lamination; top of bed brecciated, spar-cemented | 0.64 | 33.76 |
| 43 | Wackestone: thinly bedded, intensely bioturbated, gastropods, trilobites | 0.61 | 33.12 |
| 42 | Intraclastic lime rudstone: scour base, clasts of laminated dolostone | 0.14 | 32.51 |

| Unit | Description | Unit Thickness m | Cumulative Thickness m |
|---|---|---|---|
| 41 | Dolostone: laminated, undulose bedding, *in situ* brecciation and tepee structures locally, mudcracks toward top, which is brecciated and locally planed off by the overlying scour | 0.64 | 32.37 |
| 40 | Covered interval | 0.12 | 31.73 |
| 39 | Dolostone and dolomitic lime mudstone: laminated, mudcracks and small straight ripple marks near top, thinly bedded and laminated having shallow scours and mudcracks downward, some lime mudstone layers near base, plus rare gastropods; sharp base | 1.54 | 31.61 |
| 38 | Wackestone–packstone: thinly bedded, highly bioturbated in some layers, lenses of gastropods common, shallow scours common, lenses of rippled, skeletal intraclastic grainstone common in lower 1 m | 1.80 | 30.07 |
| 37 | Lime mudstone–dolostone: nodular bedding, wavy lamination, intraclastic lenses | 0.32 | 28.27 |
| 36 | Covered interval | 1.89 | 27.95 |
| 35 | Wackestone–packstone–dolostone: 88 cm of thinly bedded, bioturbated wackestone having packstone as lenses and thin layers composed of intraclasts and skeletal debris including gastropods, cephalopods, brachiopods and trilobites, top of bed is irregular, sharp base, no basal rudstone; 20 cm dolostone at top | 1.08 | 26.06 |
| 34 | Dolostone: thinly bedded, laminated and flaser bedded, scours | 0.54 | 24.98 |
| 33 | Stromatolitic boundstone: large diameter mounds composed of smooth laminar mat, local bioturbation; surrounded by thin-bedded dolomitic lime mudstone | 0.17 | 24.44 |
| 32 | Wackestone and dolomitic lime mudstone: scour base, bioturbation overlain by flaser and wavy bedding, lamination and planar thin bedding, rare gastropods, mudcracks | 0.95 | 24.27 |
| 31 | Dolostone: thin bedded, laminated, mudcracks | 0.40 | 23.32 |
| 30 | Wackestone–packstone: bioturbated, well bedded, brachiopods, gastropods and trilobites | 0.46 | 22.92 |
| 29 | Dolostone: lamination, dolomite-cemented vugs | 0.31 | 22.46 |
| 28 | Dolostone and lime mudstone: bioturbated dolostone in lower 65 cm passing up into 35 cm dolomitic parted limestone, thin bedding, planar lamination, mudcracks at several levels, some rhomboid ripple marks, intraclastic calcirudite | 1.00 | 22.15 |
| 27 | Boundstone: large diameter, steep-sided, flat-topped mounds, internal structure obscure, skeletal remains common including gastropods, straight cephalopods, and trilobites, locally mounds are planed off by erosion surfaces | 0.27 | 21.15 |
| 26 | Wackestone with packstone lenses: bioturbated, thin bedded, dolomitic, size-sorted gastropod-rich lenses of wackestone–packstone upward, skeletal packstone with trilobites, brachiopods and gastropods | 0.40 | 20.88 |
| 25 | Dolostone and dolomitic lime mudstone: dolostone and dolomitic lime mudstone upward, lenticular and flaser bedded, locally brecciated top | 0.36 | 20.48 |
| 24 | Oolitic grainstone: sharp base, fine-medium grained, internal planar bedding, rippled top with large sinuous ripple marks, some gastropods, silicified top; 060 and 185° ripple crest orientation | 0.22 | 20.12 |

| Unit | Description | Unit Thickness m | Cumulative Thickness m |
|---|---|---|---|
| 23 | Dolostone and wackestone: basal dolostone having wavy and flaser lamination, wackestone is nodular, thin bedded extensively dolomitized with extensive bioturbation, some brachiopods and straight ripple marks | 0.50 | 19.90 |
| 22 | Covered interval: includes dolomitized 32-cm-thick intraformational, edgewise lime rudstone with bioturbated wackestone lenses | 0.50 | 19.40 |
| 21 | Dolostone: planar laminated and thinly bedded | 0.28 | 18.90 |
| 20 | Boundstone: isolated 130-cm-diameter mounds, structure obscure, fossils in mounds including gastropods, straight cephalopods, brachiopods and trilobites; mounds surrounded by thinly bedded dolostone; limestone replaced abruptly by grey dolostones with abundant development of sparry dolomite, channel porosity and pseudo-crossbedding | 0.62-1.09 | 18.62 |
| 19 | Wackestone–packstone: rubbly weathering; thinly bedded, bioturbated, lenses of skeletal packstone and intraclastic calcirudite, brachiopods, gastropods, trilobites, top 24 cm replaced by crystalline and vuggy dolostone | 4.34 | 17.53 |
| 18 | Mudstone–wackestone: dolomitic, laminated and nodular, parted limestone with some burrowed layers | 0.57 | 13.19 |
| 17 | Wackestone: planar to wavy, thin bedding, some gastropods, some bioturbation | 1.18 | 12.62 |
| 16 | Covered interval | 0.25 | 11.44 |
| 15 | Wackestone with dolostone layers: smooth thin bedding, lamination and flaser, some trails, intraclastic packstone lenses and angular mudchip breccias suggesting penecontemporaneous *in situ* breakup of lithified carbonate, small ripple marks, some linear to sinuous rill marks | 1.73 | 11.19 |
| 14 | Wackestone with packstone lenses: thinly bedded, bioturbated, dolomitic laminae and flaser, skeletal packstone lenses contain gastropods, brachiopods and trilobites, ripple marks locally | 0.34 | 9.46 |
| 13 | Lime mudstone: dolomitic parted limestone and shale partings, flaser bedding, lamination, some crosslamination, small ripple marks, rill marks, layers of intraclastic pavement, minor bioturbation, some skeletal packstone lenses, wrinkle marks, some mudcracks, fine rhomboid cracks due to brittle compaction over mounds beneath | 1.93 | 9.12 |
| 12 | Lime mudstone, dolostone, shale and boundstone: thinly bedded to laminated, smooth to irregular bedding planes, some mudcracks, wrinkle marks, irregular, lobate stromatolite mounds up to 1 m in diameter and 30 cm high, mounds consist of delicate stacked and linked hemispheroids | 1.49 | 7.19 |
| 11 | Boundstone: dark-grey to grey, circular to elliptical-shaped, mounds, 15 to 30 cm high, up to 0.6 to 3.0 m in diameter with smooth flat to gently arched tops and recumbent margins, of fine continuous laminite sheets; mounds surrounded by cryptalgal laminite, laminated lime-mudstone and shale | 0.45 | 5.70 |
| 10 | Shale, dolostone and lime mudstone: laminated, mudcracked | 0.17 | 5.25 |
| 9 | Boundstone: large mounds of columnar and irregular bulbous, linked to stacked hemispheroids in light-grey, fine limestone, surrounded and capped by thin-bedded and laminated, lime mudstone and green-grey shale | 0.74 | 5.08 |
| | Covered interval: in sandy cove; only minor loss of section probable | | |

| Unit | Description | Unit Thickness m | Cumulative Thickness m |
|---|---|---|---|
| | Units 1 to 8 are part of a coastal section that contain significant 'collapse' breccias making complete compilation of this stratigraphic interval difficult | | |
| 8 | Dolostone: thin bedded, locally mudcracked, small stromatolite heads | 0.15 | 4.34 |
| 7 | Dolostone: stromatolitic, buff-weathering, pale-grey, mounds of large heads of laterally-linked and stacked hemispheroids surrounded by planar-thin stratification, sparry dolomite common, chert common | 0.55 | 4.19 |
| 6 | Oolitic grainstone: limestone and dolostone, ooids, intraclasts, skeletal grains, indistinct planar bedding, bioturbated, fossils include brachiopods, gastropods, rare trilobites | 0.40 | 3.64 |
| 5 | Dolostone: buff weathering, laminated, mudcracks | 0.20 | 3.24 |
| 4 | Dolostone: stromatolitic, spaced heads of stacked hemispheroids overlying crossbedded intraclastic dolorudstone | 0.15 | 3.04 |
| 3 | Dolostone: buff weathering, mostly planar laminated, some scours and lenticular bedding near top, some edgewise intraclastic dolorudite lenses, local chert and spar filled vugs | 1.00 | 2.89 |
| 2 | Dolostones: grey, thinly bedded, mottled by light-coloured dolomitized burrows, white chert nodules, passes, laterally into breccias including brecciated ridges, finely laminated, 3-cm-thick dolostone caps unit | 1.13 | 1.89 |
| 1 | Dolostone: buff-weathering, very fine crystallinity, lamination, large mudcrack polygons, tepee structures, locally brecciated, overlies burrow mottled pale-grey, crystalline dolostone of Watts Bight Formation | 0.76 | 0.76 |
| | WATTS BIGHT FORMATION: Eddies Cove West | | |
| 12 | At Fish Point and southward, there is an apparent dip change of strata that consists essentially of 'collapse?' breccias of dolostone with apparent dip to the north. This may suggest strata is in part equivalent to Units 1 to 10 to the north of the point. Locally, brecciated dolomites pass into bedded dolomite revealing original sedimentary structures including stromatolite mounds. Approximate thickness of this section is probably about 13.95 m. Nonetheless, the section may stratigraphically overlie Unit 10 with anomalous dips because of brecciation and solution(?) collapse. Beds appear to be very thick; breccias contain large angular blocks of laminated, mottled and massive, often cherty dolostone. Sparry dolomite plus some pyrite occurs in interclast spaces. Locally limestone is noted | | |
| 11 | Dolostone–limestone: white, finely crystalline, enclosing large masses of white limestone, honey-coloured weathering, large boundstone mounds 50 cm high and wide, surrounded by bedded fossiliferous limestone, gastropods, cephalopods, chert | 1.98 | 23.41 |
| 10 | Dolostone: fine crystalline, white sparry dolomite developed parallel to thin planar bedding | 0.52 | 21.43 |
| 9 | Boundstone and skeletal packstone replaced by dolostone: large boundstone mounds of white limestone, generally obscure internal structure, possible *Epiphyton*, packstones contain oncolitic balls 10 cm in diameter, gastropods, trilobites, straight cephalopods; porous and sparry dolostone abruptly replaces limestone and passes out into more typical, non-porous, light-grey to white, fine-medium crystalline dolostone | 2.24 | 20.91 |
| 8 | Dolostone: light-grey, finely crystalline, thinly stratified, mottled; pale-grey, crystalline limestone patches retained locally | 0.90 | 18.67 |

| Unit | Description | Unit Thickness m | Cumulative Thickness m |
|---|---|---|---|
| 7 | Dolostone and stromatolite: thick beds of buff-weathering, non-porous, fine dolostone, planar laminated and thinly stratified, some spar-filled vugs, 15-cm-diameter stromatolite mounds with bulbous cryptozoan and *Collenia* at top of dolostone beds | 2.10 | 17.77 |
| 6 | Thick-bedded, stromatolitic dolostone and dolostone: stromatolites, thick bedded chert; dolostone, planar thinly stratified, chert porosity with partial sparry dolomite fill | 2.00 | 15.67 |
| 5 | Dolostone: grey, cherty, thinly stratified with spar-filled laminar porosity, fenestrae, some brecciation, possible stromatolites | 0.90 | 13.67 |
| 4 | Dolostone: thick beds of buff-weathering, light-grey, very fine to medium crystalline dolostone, rich in chert, generally non-porous but including highly porous areas especially associated with 'collapse?' breccia development, sparry dolomite forming laminae parallel to original bedding structure to give a striped rock, mottling and possible stromatolite structure locally | 2.24 | 12.77 |
| 3 | Covered interval: sandy cove | 2.19 | 10.53 |
| 2 | Dolostone: thick beds of light-grey planar lamination and thin stratification, some rusty-weathering black chert | 0.85 | 8.34 |
| 1 | Dolostone: thickly bedded, dark-grey to black, mottled, highly bioturbated, massive to more thinly stratified beds, with beds composed of large mounds of stromatolite structures and some minor beds of laminated buff-weathering, grey dolostone | 7.49 | 7.49 |

# SECTION 5

## CATOCHE FORMATION: Hawke Flat, Hawkes Bay

Section begins on the south shore at Jenkinson Point. It continues westward for 2 km along a low rocky to sandy shoreline into the inner shore of Hawke Flat.

| Unit | Description | Unit Thickness m | Cumulative Thickness m |
|---|---|---|---|
| | CATOCHE FORMATION (incomplete) | | |
| 20 | Wackestone–packstone: well bedded, fossiliferous, intensely bioturbated, small mounds 2 m from base, gastropods common, ripple marked lenses of grainstone | 5.95 | 42.62 |
| 19 | Boundstone: thrombolite mounds, 15 cm wide, oriented 200° | 0.10 | 36.67 |
| 18 | Wackestone–packstone: bioturbated, grainstone layers, gastropods common | 1.42 | 36.57 |
| 17 | Boundstone: large linear thrombolite mounds, 5 m wide, 13 m in length, composed of circular mounds 55 cm diameter, oriented 188°, molluscs common near mounds, mounds separated by 2.5 m of burrowed, dolomitic wackestone–packstone | 0.60 | 35.15 |
| 16 | Wackestone–packstone: well bedded, fossiliferous bioturbated | 1.55 | 34.55 |

| Unit | Description | Unit Thickness m | Cumulative Thickness m |
|---|---|---|---|
| 15 | Boundstone: thrombolite, mounds arranged in clusters, 50 cm wide by 100 to 200 cm long, surrounded by thin-bedded packstone, mounds contain sponges, brachiopods, cephalopods, gastropods and small and large trilobites | 0.45 | 33.00 |
| 14 | Wackestone–packstone: fossiliferous, bioturbated chert nodules, dolostone-filled joints and cracks | 2.25 | 32.55 |
| 13 | Boundstone: thrombolite, large cephalopods, sponges and trilobites | 1.14 | 30.30 |
| 12 | Wackestone–packstone: uneven thin stratification within thick beds, bioturbated, rich locally in cephalopods, plani- and high-spired gastropods, opercula and trilobites, some ripple-marked, scour-based grainstone lenses and layers | 15.00 | 29.16 |
| 11 | Boundstone–grainstone: thrombolite mounds, flat-topped 158 by 75 cm in diameter, seperated by well-bedded, fossiliferous and intraclastic grainstone, mounds rich in straight cephalopods and large trilobite | 1.17 | 14.16 |
| 10 | Wackestone–boundstone–grainstone: intensely bioturbated wackestone with 15 cm diameter, 8-cm-high mounds fringed by crosslaminated grainstone, robust trilobites | 0.85 | 12.99 |
| 9 | Wackestone–packstone: well bedded, uneven thin stratification, bioturbated, fossils, intraclastic-bioclastic grainstone layers, gastropods, brachiopods, trilobites | 5.42 | 12.14 |
| 8 | Poorly exposed interval | 0.75 | 6.72 |
| 7 | Wackestone–packstone: uneven thin stratification, bioturbation | 1.25 | 5.97 |
| 6 | Covered interval | 0.90 | 4.72 |
| 5 | Wackestone–packstone: uneven thin stratification, nodular, bioturbation, dolomitic mottle, intraformational-skeletal grainstone lenses | 1.76 | 3.82 |
| 4 | Boundstone–grainstone–wackestone: Thrombolite mounds 32 cm high and 70 cm in diameter are overlain and topped by wackestone. Traced to west, they disappear and then reappear fringed by crossbedded grainstone, associated with gastropods, large straight to curved cephalopods, sponges, crinoids, robust trilobites and brachiopods, some ripple marks | 0.55 | 2.06 |
| 3 | Grainstone: intraclastic-skeletal, thinly stratified | 0.11 | 1.51 |
| 2 | Boundstone: two thrombolite mound beds 28 and 25 cm thick, both surrounded by grainstone fringe, steep-sided, irregularly shaped 20 to 30 cm in diameter; grainstone is intraclastic and skeletal, unevenly thin bedded, rich in gastropods, cephalopds, brachiopods and trilobites | 0.53 | 1.40 |
| 1 | Mudstone–wackestone–packstone: unevenly thin bedded, bioturbated, fossiliferous, lamination near base with pockets of intraclasts, some small mounds near top | 0.87 | 0.87 |

# SECTION 6

## BOAT HARBOUR FORMATION–CATOCHE FORMATION: Barbace Point to Barbace Cove (includes Barbace Cove Member type section)

Base of section begins on Barbace Point, 2.8 km along shore from Barbace Cove. The point looks east toward Round Island. The section continues to east of Barbace Cove. Total thickness of section is approximately 66 m.

| Unit | Description | Unit Thickness m | Cumulative Thickness m |
|---|---|---|---|
| | Catoche Formation (incomplete) | | |
| 11 | Wackestone–packstone with intraclastic grainstone and rudstone lenses: thick to medium bedded, rubbly weathering; scour-based intraclastic rudstone up to 15 cm thick at base and in some instances in centres of beds; wavy and lenticular bedded packstone–wackestone and smoother, wavy, unevenly thin-bedded wackestone with dolostone drapes and burrow mottling fill rest of bed; skeletal remains include brachiopods, trilobites, eocrinoids, gastropods and straight cephalopods | 5.45 | 15.08 |
| 10 | Wackestone with dolostone layers: gastropods; poorly exposed | 0.53 | 9.63 |
| 9 | Wackestone–packstone with intraclastic grainstone rudstone lenses: uneven, lenticular bedding at first, shaly and dolostone drapes in smoother, wavy thin bedding increasing upward; bioturbation; 1- to 3-cm intraclastic–skeletal grainstone–rudstone lenses, scour-based, some crossbedded, ripple-marked; gastropods, minor trilobites | 2.29 | 9.10 |
| 8 | Intraclastic–skeletal grainstone rudstone: scour-based, packstone lenses; trilobites | 0.26 | 6.81 |
| 7 | Packstone–wackestone: wackestone with minor packstone lenses at top, bedded packstone has skeletal wackestone lenses in lower half of bed, gastropods, trilobites | 1.27 | 6.55 |
| 6 | Intraclastic grainstone–rudstone: scour base, crossbedded (thickness of bed), imbricated discoid lime intraclasts, sharp top | 0.28-0.34 | 5.28 |
| 5 | Wackestone–packstone: wackestone and packstone lenses overlain by flaser-bedded lime mudstone and dolostone (25 cm), skeletal remains include trilobites, brachiopods | 0.87 | 4.94 |
| 4 | Wackestone–packstone and minor grainstone: well-bedded, bioturbated, dolomite burrow mottling, thin bedding in wackestone; skeletal packstone rich in trilobites, eocrinoids, gastropods, brachiopods, 2- to 3-cm-thick lenses of intraclastic–skeletal grainstone near top | 2.02 | 4.07 |
| 3 | Boundstone: rubbly weathering, skeletal-rich mounds, obscure structure rich in large gastropods, straight cephalopods, eocrinoids | 0.58 | 2.05 |
| 2 | Wackestone: bioturbated, lumpy thin bedding, gastropods, cephalopods | 0.82 | 1.47 |
| 1 | Wackestone–lime mudstone: wavy, thin bedded and laminated (15 cm) at base up into bioturbated, lumpy bedding | 0.65 | 0.65 |
| | Base of Catoche Formation conformable upon Boat Harbour Formation, at point on the east side of Barbace Cove | | |
| | Boat Harbour Formation (incomplete) | | |
| | Barbace Cove Member (Units 26 to 38) | | |
| 38 | Lime mudstone: wavy and planar thin bedding and lamination, some crosslamination, ripple marks, mudcracks | 0.45 | 51.14 |

| Unit | Description | Unit Thickness m | Cumulative Thickness m |
|---|---|---|---|
| 37 | Wackestone: bioturbated, stylolites, nodular, sharp flat base | 0.91 | 50.69 |
| 36 | Shaly, dolomitic lime mudstone and dolomitic calcareous shale: mudcracks, straight symmetrical ripple marks | 0.52 | 49.78 |
| 35 | Wackestone: bioturbated, stylolites, gastropods, intraclastic packstone layers, small boundstone mounds near middle and top of bed; trilobites, sharp base | 0.83 | 49.26 |
| 34 | Dolostone and lime mudstone: shaly parting, mudcracks, cryptalgal biscuits, finely laminated, some ripple crosslamination, gradational base | 1.29 | 48.43 |
| 33 | Wackestone–lime mudstone with a few 1 to 3 cm layers of packstone: ripple marks, ladder ripple marks, gutter casts filled by dolomitic lime mudstone | 0.90 | 47.14 |
| 32 | Skeletal–intraclastic packstone and grainstone: sharp base, crossbedded, ripple marked top crosscut obliquely by narrow sinuous runoff(?) channels (gutter casts), trending 096 to 118°, ripple crests 052, 085° | 0.23 | 46.24 |
| 31 | Packstone–wackestone–mudstone: thinly interbedded, bioturbated, scour bases to packstone–grainstone beds, which are skeletal and intraclastic, reddish pebbles, ripple marks, runoff structures, molar tooth structures, gastropods, brachiopods, trilobites, large *Isotoloides* | 2.04 | 46.01 |
| 30 | Grainstone–wackestone: skeletal–intraclastic, crossbedded and ripple-marked grainstone separated by bioturbated wackestone, rich in brachiopods, gastropods, trilobites, ripple mark crests trend 095, 115° | 0.48 | 43.97 |
| 29 | Wackestone: smooth to uneven thin bedding, shaly dolomitic lime mudstone drapes, bioturbated | 0.42 | 43.49 |
| 28 | Grainstone: crossbedded, ripple-marks, some planed off, fossiliferous | 0.28 | 43.07 |
| 27 | Lime mudstone to grainstone: flaser- and wavy-bedded to flat-bedded dolomitic lime mudstone with 10- to 20-cm intraclastic packstone or crossbedded, skeletal–intraclastic grainstone, shale drapes in crossbeds, ripple marks; crossbed direction 110°, 115° | 1.97 | 42.79 |
| 26 | Dolostone: laminated and thin bedded, mudcracks in upper 100 cm; flaser- and wavy-bedded dolostone and lime mudstone below with minor mudcracked shaly dolostone beds (18 cm), locally some bioturbated wackestone with scattered trilobites | 2.58 | 40.82 |
| | Lower Member | | |
| 25 | Stromatolitic dolostone: large, steep-sided, 2 m diameter mounds, surrounded by bedded dolostone; LLH structure, top is silicified and extensively brecciated, marking the site of the Boat Harbour disconformity | 0.65 | 38.24 |
| 24 | Dolostone: grey, thick bedded, poorly exposed; some bioturbation | 2.57 | 37.59 |
| 23 | Stromatolitic dolostone: mounds up to 1 m in size, steep-sided, composed of digitate structures, medium crystallinity | 0.78 | 35.02 |
| 22 | Dolostone: buff-grey, well bedded, lenticular and flaser bedded, some *Chondrites* in layers, scour-and-fill, intraclastic breccias, some ripple crosslamination, some mudcracks and tepee structures, 13-cm stromatolite bed of LLH midway through unit | 2.97 | 34.24 |

| Unit | Description | Unit Thickness m | Cumulative Thickness m |
|---|---|---|---|
| 21 | Dolostone: well bedded, very fine crystallinity, thin bedded internally, bioturbated | 1.21 | 31.27 |
| 20 | Dolostone: flaser and lenticular bedded, scour-and-fill, ripple marks, some mudcracks near top, minor bioturbated layers, infrequent to rich development of quartz-filled vugs, irregular pitted top to bed | 1.73 | 30.06 |
| 19 | Stromatolitic dolostone: two beds of mounds, each surrounded by bedded dolostone, and upper bed passing into intensely bioturbated dolostone in which spherical depressions occur, chert, quartz-filled vugs | 0.64 | 28.33 |
| 18 | Dolostone: mottled and thin bedded at base (12 cm) overlain by flaser- and lenticular-bedded dolostone (24 cm), some linear runoff structures, rest of bed is composed of bioturbated, thin-bedded dolostone with minor stromatolite mounds | 1.36 | 27.69 |
| 17 | Stromatolitic dolostone: 20 cm diameter mounds surrounded and covered by ripple- and flat-bedded dolostone | 0.15 | 26.33 |
| 16 | Lime mudstone–dolostone: bioturbated, gastropod-rich, nobbly thin-bedded dolostone (16 cm) overlain by smooth thin-bedded and then flaser- and lenticular-bedded lime mudstone and dolostone, some layers of *Chondrites* and lenses of intraclastic lime rudstone | 1.16 | 26.18 |
| 15 | Stromatolitic dolostone: massive bed with extensive development of dolomite spar, undulose mound top, 2-m diameter mounds surrounded by bioturbated, gastropod-rich, thinly bedded dolostone | 0.49 | 25.02 |
| 14 | Dolostone: flat bedded and bioturbated with sparry dolomite in bedding at base (125 cm) overlain by flaser- and lenticular- bedded dolostone | 2.15 | 24.53 |
| 13 | Covered interval | 0.75 | 22.38 |
| 12 | Lime mudstone–wackestone–dolostone: three 0.82 to 1.10 m sequences of bioturbated, stylolitic, thinly bedded to massive lime mudstone–wackestone overlain by flaser- and lenticular-bedded lime mudstone replaced upward by dolostone, some gastropods, some bioturbated layers in flaser-bedded limestones and dolostones | 2.89 | 21.63 |
| 11 | Covered interval: cobble beach | 1.46 | 18.74 |
| 10 | Dolostone: well bedded, bioturbated, thinly bedded, gastropods, some flat-topped boundstone mounds | 0.75 | 17.28 |
| 9 | Dolostone: lenticular and flaser bedded, minor bioturbation, (60 cm) overlying smooth thin-bedded (65 cm) and bioturbated, thin-bedded dolostone | 2.16 | 16.53 |
| 8 | Dolostone: flaser bedded (16 cm) at top, rest is well-bedded, bioturbated dolostone, fine crystallinity, laminar and crosscutting developments of white sparry dolomite | 3.11 | 14.37 |
| 7 | Dolostone: fine crystallinity, thinly bedded, lenticular and flaser bedded, minor bioturbation, some lenses of intraclastic dolorudite, mudcracks; traced laterally to Barbace Point foghorn, the dolostone becomes well bedded but structure is obscure, a 1-m covered interval also occurs | 2.90 | 11.26 |
| 6 | Stromatolitic dolostone: sparry dolomite developed in mounds, 25 cm diameter mounds, in nests up to 2 m in diameter, mound shape is irregular | 0.39 | 8.36 |

| Unit | Description | Unit Thickness m | Cumulative Thickness m |
|---|---|---|---|
| 5 | Lime mudstone laterally replaced by epigenetic dolostone: well-bedded, lime mudstone internally of smooth thin bedding overlying flaser bedding, some ripple marks, wrinkle marks, gutter casts, intraclastic layers formed by in situ breakup, rare gastropods, some bioturbation; abrupt transition across joints into fine crystalline dolostone with sparry dolomite developed in tension joints | 2.61 | 7.97 |
| 4 | Covered interval: pebble beach, possibly contains minor fault | 0.50 | 5.36 |
| 3 | Dolostone: well bedded, internally massive, or thin and lenticular bedded, some bioturbation, rare gastropods, some mudcracks, sparry dolomite in channel porosity parallel to bedding | 2.61 | 4.86 |
| 2 | Dolostone: well bedded, massive, bioturbated, hummocky top suggesting some stromatolites | 0.60 | 2.25 |
| 1 | Dolostone: lenticular and flaser bedded, minor bioturbation with rare gastropods; covered base at point | 1.65 | 1.65 |

Most of the dolostone in Units 1 to 24 are considered to be epigenetic in origin. The dolomitization can be related to numerous small faults and open folds that affect this part of the succession north of Barbace Point.

# SECTION 7

## CATOCHE FORMATION–BARBACE COVE MEMBER, BOAT HARBOUR FORMATION: Savage Island

The section is located on the west shore and around the northern point of the island. Outcrop in the Catoche Formation is sporadic. Total thickness of section is approximately 58.5 m.

| Unit | Description | Unit Thickness m | Cumulative Thickness m |
|---|---|---|---|
| | CATOCHE FORMATION (incomplete) | | |
| 13 | Wackestone–packstone: dark-grey, bioturbated, dolomite-mottled, fossiliferous, large gastropods and straight cephalopods; grainstone bed 1 m from top | 7.50 | 56.66 |
| 12 | Covered interval | 2.05 | 49.16 |
| 11 | Wackestone–packstone: typically bedded, bioturbated, dark grey | 2.30 | 47.11 |
| 10 | Covered interval | 6.20 | 44.81 |
| 9 | Wackestone–packstone: well bedded, bioturbated, dark grey | 5.20 | 38.61 |
| 8 | Covered interval | 12.00 | 33.41 |
| 7 | Wackestone-packstone: bedded, bioturbated | 1.00 | 21.41 |
| 6 | Covered with intermittent poorly exposed limestone ledges | 14.00 | 20.41 |
| 5 | Wackestone–packstone with laminated packstone layer, dolomitic parted limestone, bioturbated, some cover | 1.70 | 6.41 |

| Unit | Description | Unit Thickness m | Cumulative Thickness m |
|---|---|---|---|
| 4 | Boundstone: mounds 35 cm in diameter irregular in shape, rich in sponges, cephalopods and gastropods; grainstone fringe | 0.15 | 4.71 |
| 3 | Wackestone–packestone and dolomitic parted limestone: thinly stratified, skeletal wackestone–packstone, rubbly weathering, 50 cm parted limestone 20 cm from top | 3.29 | 4.56 |
| 2 | Boundstone: mounds associated with opercula, gastropods and trilobites | 0.27 | 1.27 |
| 1 | Wackestone–packstone, skeletal, thinly stratified | 1.00 | 1.00 |
| | BOAT HARBOUR FORMATION (incomplete) | | |
| | Barbace Cove Member | | |
| 13 | Dolomitic lime-mudstone: laminated, mudcracked | 0.23 | 12.95 |
| 12 | Mudstone–wackestone–packstone: skeletal, thinly stratified mudstone | 0.54 | 12.72 |
| 11 | Dolomitic lime mudstone: mudcracked, laminated, wavy thin stratification at top grading into overlying bed, not well exposed | 1.07 | 12.18 |
| 10 | Rudstone–mudstone: intraclastic–skeletal rudstone with scour base overlain by thinly stratified, bioturbated, skeletal, mudstone–wackestone–packstone | 0.55 | 11.11 |
| 9 | Boundstone–wackestone: 12-cm mound bed overlain by 20 cm of dolomitic skeletal wackestone with shale drapes at the top | 0.32 | 10.56 |
| 8 | Dolomitic limestone: mudcracked, laminated, lime mudstone, increasingly dolomitic upwards | 0.78 | 10.24 |
| 7 | Lime mudstone: bioturbated, thinly stratified, wavy bedded, grades up over 2 to 3 cm into Unit 8 | 2.10 | 9.46 |
| 6 | Lime mudstone: dolomitic, flaser bedded | 0.24 | 7.36 |
| 5 | Wackestone–grainstone: bioturbated, shaly wackestone (parted limestone) intercalated with several 5- to 10-cm-thick beds of intraclastic–skeletal grainstone. These beds have erosive bases, planar- to ripple-marked tops and contain brachiopods and the trilobite *Isotoloides* | 2.53 | 7.12 |
| 4 | Shaly lime mudstone: uneven thin stratification, some dolomitic bioturbation, grainstone lenses, wrinkle marks, mudchip pavements | 1.40 | 4.59 |
| 3 | Dolostone and lime mudstone: shaly, laminated, micro-wrinkle marks, mudcracks | 0.59 | 3.19 |
| 2 | Dolostone: yellow to buff weathering, thin stratified to laminated, scours, mudcracks, locally filled with green shale in lower 1 m | 1.34 | 2.60 |
| 1 | Dolomitic limestone: bioturbated, poorly exposed, base covered by sea | 1.26 | 1.26 |

# SECTION 8

## CATOCHE FORMATION: Bustard Cove to Back Arm (stratotype)

The section begins at Hunters Point, 3.4 km west of Eddies Cove West and continues around Bustard Cove to the east shore of Back Arm, where the top of the unit occurs 0.6 km north of Port au Choix. Main units correspond to descriptions and graphic logs shown in Knight and James (1988).

Top of the formation is apparently conformable below rocks of the Aguathuna Formation.

| Unit | Description | Unit Thickness m | Cumulative Thickness m |
|---|---|---|---|
| 14g | Dolostone: tan-grey weathering, thickly bedded, massive to locally highly porous, sparry dolomite developed in vug porosity and along bedding, burrow mottling common, porosity increases toward centre of beds, some minor pockets of limestone | 10.87 | 160.34 |
| 14f | Covered interval | 1.68 | 149.47 |
| 14e | Dolostone: thick bedding, porosity and sparry dolomite developed extensively in middle of beds, some 'psuedobreccia' (Cummings, 1968), sparry dolomite completely sealing porosity in some beds, local burrow mottling preserved, tighter fine crystalline dolostone toward top and base of beds with mottling, discontinuous thin bedding, shale partings | 4.20 | 147.79 |
| 14d | Covered interval | 2.28 | 143.59 |
| 14c | Dolostone: thickly bedded, tan-grey weathering, black, dark grey to light grey, porosity best developed in middle of bed, but commonly closed by widespread development of white sparry dolomite nucleated around small and large dolostone rafts, outer zones of beds of tight, nonporous, mottled to massive or thinly bedded, fine crystalline dolostone | 5.06 | 141.31 |
| 14b | Covered interval | 1.02 | 136.25 |
| 14a | Dolostone: thickly bedded, tan-grey weathering, dark grey to grey, burrow mottling common, porosity low to locally extensive in centre of beds, white sparry dolomite commonly fills porosity; outer parts of beds of tighter darker coloured dolostone, rare gastropod remains seen | 8.99 | 135.23 |
| 13 | Covered interval under beach and glacial drift near entrance to Back Arm: Interval calculated from structural cross-section and by geometric calculation—distance angle of dip. Average thickness is shown | 33.00 | 126.24 |
| 12e | Wackestone—lime mudstone with skeletal packstone lenses and dolomitized peloidal packstone layer: well-bedded, mottled, dolomite drapes and burrows, fossils include trilobites, gastropods, minor large cephalopods | 3.00 | 93.24 |
| 12d | Covered interval | 0.79 | 90.24 |
| 12c | Wackestone with packstone lenses: well-bedded, bioturbated, large gastropods; skeletal packstone lenses of skeletal—traclastic grainstone with rippled tops; fossils include high-spired and planispired gastropods, abundant trilobite fragments, *Receptaculites*, possible eocrinoid remains | 8.24<br>1.49 | 89.45 |
| 12b | Covered interval: at neck of cove, wackestone beds ≈1 m thick in cove to east | 1.16 | 87.96 |
| 12a | Wackestone with packstone layers and lenses: well-bedded, dolomitic, intensely bioturbated in lower beds, scattered gastropods, some flaser of lime mudstone; ripple-marked lenses of skeletal packstone; fossils include large trilobites, gastropods, some brachiopods; 4- to 6-cm grainy packstone bed at top | 1.80 | 86.80 |

| Unit | Description | Unit Thickness m | Cumulative Thickness m |
|---|---|---|---|
| 11 | Boundstone: two or more beds, obscure internal structure, outer zone of large mounds consisting of well-cemented grainstone; fluorite; mounds contain large straight cepahlopods, large and small trilobites, plani- and high-spired gastropods, sponges?, *Receptaculites*, possible stromatolite in base of mound, mounds become smaller as traced to south | 1.00 | 85.00 |
| 10p | Wackestone with minor boundstone, grainstone and packstone: wackestone is well bedded, with intensely and moderately bioturbated layer, gastropods common; lenses of intraclastic skeletal grainstone and packstone with uneven thin planar stratification and some crossbedding, starved ripple marks, trilobites; boundstone mounds; mounds isolated surrounded by ripple-marked intraclastic skeletal grainstone lenses; wackestone replaced laterally by dolostone | 2.63 | 84.00 |
| 10n | Covered interval: gravelly cove | 0.70 | 81.37 |
| 10m | Wackestone with packstone layers: well bedded, uneven thin bedding internally, bioturbated; intraclastic packstone–grainstone layers and lenses, scour base, ripple topped, internally crosslaminated; unit replaced sharply along strike by epigenetic dolomite with white sparry dolomite developed parallel to thin bedding | 3.06 | 80.67 |
| 10l | Wackestone–packstone: well-bedded bioturbated wackestone with uncommon to common packstone layers and lenses, some small lime mudstone mounds, stylolites, large orientated cone-shaped and straight cepahlopods, large gastropods, dolomitic burrow mottling and replacement of some thin bedding; intraclastic skeletal packstone generally has crude internal stratification, scour or gradational bases, rippled-marked tops, starved ripple marks, trilobites, brachiopods, planispiral gastropods, cephalopods. | 5.99 | 77.61 |
| 10k | Boundstone–wackestone–grainstone: small pie-shaped mounds, associated with intraclastic–skeletal grainstone and wackestone, ripple marks, large cephalopods, brachiopods, high-spired and planispired gastropods, trilobites; fluorite in calcite-filled vugs | 0.06 | 71.62 |
| 10j | Wackestone–packstone: well-bedded, bioturbated wackestone, locally rich in gastropod opercula, vugs; lenticular packstones composed of intraclasts and skeletal grains; ripple marks, some crossbedding, some cepahlopod-rich; trilobites, brachiopods | 4.49 | 71.56 |
| 10i | Covered interval | 0.55 | 67.07 |
| 10h | Intraclastic grainstone: scour base, obscure internal structure; fluorite | 0.10 | 66.52 |
| 10g | Wackestone–packstone: well-bedded, bioturbated, rubbly weathering wackestone, dolomite and calcite spar in small vugs, small lime mudstone mounds and gastropod-rich mounds, chert nodules, some dolomitic lime mudstone layers; packstone-grainstone is lenticular, composed of skeletal intraclasts and coated grains, scour base, straight ripple mark; trilobites; fluorite | 2.24 | 66.42 |
| 10f | Wackestone capped by thin grainstone–packstone: lightly bioturbated, gastropods and cephalopods, some ripple marks; grainstone crossbedded | 0.82 | 64.18 |
| 10e | Wackestone–packstone capped by thin grainstone: bioturbated wackestone with some gastropods, dolomite burrow mottling; lenses and layers of skeletal intraclastic packstone, some grainstone, scour bases, crossbedded, straight to catenary ripple marks, 5 cm grainstone at top | 2.11 | 63.36 |
| 10d | Wackestone–packstone–grainstone: bedded bioturbated wackestone, stylolites; skeletal–intraclastic packstones; ripple-marked grainstone beds, straight to catenary ripple marks, scour bases; brachiopods, high-spired and planispiral gastropods, cephalopods, trilobites; undulose bedding at top of unit | 2.44 | 61.25 |

| Unit | Description | Unit Thickness m | Cumulative Thickness m |
|---|---|---|---|
| 10c | Covered interval: beach | 0.35 | 58.81 |
| 10b | Wackestone–packstone: well-bedded, bioturbated wackestone, stylolites, gastropods; scour-based, lenticular packstone and grainstone, ripple marks, skeletal–intraclastic grainstone–packstone common in upper 24 cm, trilobites, brachiopods, gastropods | 3.23 | 58.46 |
| 10a | Covered interval: gravel beach | 0-0.40 | 55.23 |
| 9 | Boundstone: rubbly weathering, obscure internal structure, irregular to spherical metre-sized mounds, gastropods, cephalopods, trilobites | 0.59 | 54.83 |
| 8e | Wackestone–packstone interspersed with skeletal–intraclastic grainstone and some intraclastic rudite, scour-based lenses and layers, trilobites, brachiopods, gastropods | 6.08 | 54.24 |
| 8d | Covered interval | 0.90 | 48.16 |
| 8c | Wackestone with minor packstone lenses: rubbly weathering, massive bedded, stylolites, some gastropods; packstone lenses with trilobites, brachiopods, high-spired and planispired gastropods, cephalopods | 1.57 | 47.26 |
| 8b | Covered interval | 1.80 | 45.69 |
| 8a | Wackestone: intensely bioturbated | 0.55 | 43.89 |
| 7 | Boundstone: oriented, separated, linear mounds 6 m wide and up to 75 m long, obscure internal structure, locally rich in large-bodied shelly fauna, straight to curved cephalopods, high- and low-spired and planispired gastropods, sponges, eocrinoids, brachiopods and trilobites; thin-bedded skeletal wackestone and crossbedded grainstone between mounds, some large straight ripple marks | 0.30 | 43.34 |
| 6m | Wackestone–lime mudstone: well-bedded, bioturbated, dolomite mottles, large broad scours, metre-scale undulating bedding, lenses rich in large straight cephalopods, some resistant ledges of intraclastic packstone rich in ostracods, large cephalopods, gastropods and trilobites | 3.61 | 43.04 |
| 6l | Lime mudstone–wackestone: stylolites, fossils uncommon, bioturbation, well bedded | 1.65 | 39.43 |
| 6k | Covered interval: gravel beach, storage area for lobster pots | 1.00 | 37.78 |
| 6j | Wackestone: uneven thin stratification, gastropods, dolomite burrow mottling | 1.46 | 36.78 |
| 6i | Wackestone–packstone with some grainstone layers: wackestone well-bedded and bioturbated, dolomitic burrow mottling, gastropods and cephalopods, some small boundstone mounds; packstones and grainstones of intraclasts, algal-coated grains and skeletal remains, starved ripple marks, some major scours, gastropods, trilobites, *Receptaculites*, some brachiopods | 2.19 | 35.32 |
| 6h | Wackestone–packstone capped by grainstone: 30 to 90 cm beds; wackestone is well-bedded, bioturbated, fossiliferous, large cephalopods common; packstone–grainstone lenses, scour-based, crossbedded, ripple-topped, lime mudstone drapes over ripple marks, intraclastic and skeletal, trilobites, plani- and high-spired gastropods | 2.16 | 33.13 |
| 6g | Wackestone–lime mudstone: well-bedded, dolomite drapes and burrow mottling | 0.49 | 30.97 |

| Unit | Description | Unit Thickness m | Cumulative Thickness m |
|---|---|---|---|
| 6f | Covered interval | 0.46 | 30.48 |
| 6e | Wackestone–packstone: well-bedded, gastropods, dolomitic burrow mottling; packstone, intraclastic and rich in gastropods; upper 72 cm poorly exposed | 1.90 | 30.02 |
| 6d | Covered interval | 0.26 | 28.12 |
| 6c | Wackestone: bioturbated, uneven thin stratification, gastropods | 0.38 | 27.86 |
| 6b | Covered interval: sandy and muddy cove | 3.14 | 27.48 |
| 6a | Wackestone–packstone: gastropod-rich, intensely bioturbated wackestone, large cephalopods; scour-based intraclastic–skeletal-packstone, gastropods, trilobite, eocrinoids | 1.02 | 24.34 |
| 5h | Grainstone: intraclastic–skeletal, thin internal bedding, scour base | 0.13 | 23.32 |
| 5g | Wackestone–boundstone: skeletal wackestone, uneven bedding, large cephalopods and gastropods, intensely bioturbated; 35-cm-high and diameter boundstone mounds surrounded by skeletal packstone replace wackestone as beds are traced east into cove | 0.24-0.35 | 23.19 |
| 5f | Lime mudstone: uneven thin stratification, poorly fossiliferous and bioturbated in basal half, some skeletal packstone layers near top, trilobites | 0.09 | 22.84 |
| 5e | Lime mudstone: shaly, flaser bedded, lamination, mudcrack polygons near top | 0.70 | 22.75 |
| 5d | Grainstone: scour-based, crossbedded, intraclastic and skeletal, ripple-marked top, local edgewise breccias, lime mudstone drapes, large trilobite fragments, straight cephalopod eocrinoids | 0.13 | 22.05 |
| 5c | Wackestone–lime mudstone–packstone with grainstone lenses: smooth wavy bedded wackestones–lime mudstone, bioturbation moderate, dolomitic mottling and thin beds; lenses of skeletal and intraclastic packstone and grainstone: large gastropods and cephalopods, high-spired gastropods, trilobites, some straight ripple marks | 2.78 | 21.92 |
| 5b | Grainstone: ripple marked, rich in gastropods | 0.10 | 19.14 |
| 5a | Wackestone and packstone lenses and layers: well-bedded, bioturbated, dolomite burrow mottling; skeletal grainstone and packstone lenses 1 to 5 cm thick, scour based, some ripple marks; trilobite, high-spired gastropods, cephalopods | 2.32 | 19.04 |
| 4f | Wackestone–lime mudstone with minor packstone lenses: moderately bioturbated, uneven thin stratification, gastropods, some trilobites | 1.66 | 16.72 |
| 4e | Wackestone with skeletal packstone lenses and minor grainstone: uneven thin stratification, variable bioturbation with poorly fossiliferous and lightly bioturbated wackestone, starved ripples in grainstone lenses, gastropods, brachiopods, straight cephalopods, trilobites in upper 100 cm | 2.86 | 15.06 |
| 4d | Intraclastic calcirudite: channel scour base, edgewise orientation of clasts locally, large trilobite fragments, gastropods and straight cephalopods, wackestone layers in conglomerate | 0.32-0.40 | 12.20 |
| 4c | Wackestone and packstone–grainstone lenses and layers: bioturbated, thinly stratified wackestones, dolomite mottling, gastropods, complete eocrinoid; packstone–grainstone lenses and layers, 2 to 10 cm thick, every 10 to 35 cm, skeletal and intraclastic, scour bases, rippled tops, starved ripples, reddened lime mudstone intraclasts, trilobites, brachiopods, gastropod-rich, cephalopods | 0.82 | 11.80 |

| Unit | Description | Unit Thickness m | Cumulative Thickness m |
|---|---|---|---|
| 4b | Lime mudstone–wackestone with packstone lenses: well-bedded, smooth to uneven depending upon intensity of bioturbation, dolomitic layers and mottling, gastropods, eocrinoids | 1.25 | 10.98 |
| 4a | Boundstone–wackestone–lime mudstone: obscure structure to mounds, surrounded by well-bedded, bioturbated, fossiliferous wackestone, gastropods, cephalopods | 0.20 | 9.73 |
| 3d | Covered interval; beach | 1.56 | 9.53 |
| 3c | Wackestone–packstone: well-bedded, skeletal, bioturbated, dolomitic mottle, brachiopods, cephalopods, trilobites, gastropods, eocrinoids, intraclasts and coated grain in 1 to 3 cm packstone layers | 0.82 | 7.97 |
| 3b | Covered interval: beach | 1.96 | 7.15 |
| 3a | Wackestone with packstone: well bedded, thin uneven stratification, dolomitic burrow mottling, some small boundstone mounds; scour-based lenses of skeletal packstone, high-spired and planispired gastropods, cephalopods | 2.08 | 5.19 |
| 2 | Boundstone: mounds, obscure internal structure, rich in skeletal remains, trilobites, sponges, eocrinoids, large gastropods and cephalopods; mounds end to south side of Hunters Point and pass into wackestone rich in gastropod opercula | 1.65 | 3.11 |
| 1b | Wackestone–packstone: rubbly weathering, thin stratification, rich in gastropods and straight cephalopods | 0.85 | 1.46 |
| 1a | Wackestone–packstone with lime mudstone near top: skeletal, massive, rubbly weathering, to thinly stratified wackestone with trilobites, ostracods and gastropods, upper 20 cm are of laminated, dolomitic lime mudstone with some thin lenses of skeletal packstone | 0.61 | 0.61 |

Base of Catoche Formation, on north side of Hunters Point. Conformable upon Unit 122 of Boat Harbour Formation, Eddies Cove West section (Section 4, page 107). Total thickness of Catoche Formation is 160.37 m.

# SECTION 9

## CATOCHE FORMATION: Catoche Point, Port au Choix Peninsula to Blanche Point, Pointe Riche Peninsula (Reference Section)

The section occurs along the rocky shoreline of the western side of the Port au Choix Peninsula from Catoche Island south to Laignet Point. The section then continues south of the mouth of the cove Port au Choix, south to Blanche Point.

The top of the formation is concealed beneath a long covered interval south of Blanche Point. A number of northeastward- and southeastward-striking faults dissect the lower strata of the section. Main units correspond to descriptions and graphic logs shown in Knight and James (1988).

| Unit | Description | Unit Thickness m | Cumulative Thickness m |
|---|---|---|---|
| 18 | Dolostone: dark grey to grey, fine to medium crystalline, thick bedded, massive weathering, bituminous, vuggy, with beds of 'pseudobreccia', abundant secondary porosity lined by white saddle dolomite, some beds contain ghosts of gastropods and cephalopods, burrow mottling | 38.85 | 161.28 |
| 17 | Covered interval: mouth of Port au Choix Cove; locally small outcrops of limestone composed of bioclastic wackstone with *Receptaculites* | 10.0 | 122.43 |

| Unit | Description | Unit Thickness m | Cumulative Thickness m |
|---|---|---|---|
| 16d | Wackestone–packstone: dolomitic burrow mottling, some intraclastic–bioclastic grainstone lenses, some beds extensively dolomitized, coated grains, peloids, *Receptaculites* crinoids, trilobites, gastropods and cephalopods, graptolites 2.5 m from base | 14.80 | 112.43 |
| 16c | Covered interval: in narrow channel to Laignet Point Island | 1.00 | 97.63 |
| 16b | Wackestone with a few grainstone and packstone lenses and layers: bioturbated, fossiliferous, graptolites 2 m from base and at top, dolomitized in some beds, cut by northeast-trending faults that downthrow to east, throw unknown | 6.05 | 96.63 |
| 16a | Wackestone–packstone: fossiliferous, bioturbated, dolomite lines vugs, common 20-cm-packstone beds at top rich in straight cephalopods, gastropods and some small mounds | 1.65 | 90.58 |
| 15b | Dolomitic wackestone: lime mottled, massive with crude stratification, beds undulate over mounds | 0.35 | 88.93 |
| 15a | Boundstone and wackestone: rubbly weathering, dark-grey limestone composed of very large thrombolite mounds having large sponges, cephalopods, gastropods and other fossils and of calcite-cemented to dolomitized grainstone in intermound areas and fringing mounds, grainstones grade laterally into bioturbated, bioclastic wackestone–packstone, green-grey, buff-weathering dolostone filling northeast-trending fractures | 1.80 | 88.58 |
| 14h | Packstone–wackestone: dark grey, well-bedded, rubbly weathering, bioturbated; grainstone common but decreasing upward, they are planar stratified and carry ripple marks (crests 194, 186, 170, 035), small 5 to 20 cm high, 15 to 60 cm diameter mounds 2.5 m from top | 6.16 | 86.78 |
| 14g | Wackestone–packstone with ripple marked grainstone lenses, some ripples planed off (010°, 160° ripple crest orientation) | 0.75 | 80.62 |
| 14f | Wackestone: bioturbated, pockets of crosslaminated grainstone, gastropods, small egg-cup mounds 3 to 5 cm diameter, 3 cm high | 0.18 | 79.87 |
| 14e | Wackestone–packstone: uneven thin stratification, burrow mottling, gastropods, grainstone lenses, rare, small centimetre-sized egg-cup mounds | 3.35 | 79.69 |
| 14d | Covered interval | 1.27 | 76.34 |
| 14c | Wackestone–packstone: bioturbated, argillaceous, lenses and layers of grainstone and packstone, some small mounds, large straight cephalopods | 2.27 | 75.07 |
| 14b | Dolomitic lime wackestone: mottled | 0.65 | 72.80 |
| 14a | Wackestone–packstone: uneven thin stratification, bioturbated, argillaceous, skeletal remains | 1.27 | 72.15 |
| 13 | Boundstone–wackestone packstone: 1.0 to 2.2 m diameter, 40 cm high, scattered, irregular shaped, sponge-thrombolite mounds surrounded by thin-bedded wackestone–packstone | 0.30 to 0.40 | 70.88 |
| 12 | Wackestone–packstone with grainstone lenses in elongate sinuous scours: main lithology is thinly bedded, bioclastic, burrow-mottled, gastropods | 5.65 | 70.48 |
| 11 | Boundstone: thrombolite-sponge mounds rich in large cephalopods, gastropods, *Archeoscyphia* and trilobites, grainstone accumulated between small mounds that make up large mound banks, with 30-cm-synoptic relief separated by 20-m-wide channels filled by interbedded, thinly bedded, wackestone, packstone and grainstone | 1.30 | 64.83 |

| Unit | Description | Unit Thickness m | Cumulative Thickness m |
|---|---|---|---|
| 10 | Wackestone–packstone with grainstone layers and lenses: dark-grey thinly stratified and bioturbated wackestone–packstone at 5.2 m irregular crosscutting surface fault overlain by several grainstone beds, some grainstones are ripple marked, and formed hardgrounds, ripples planed off, (155°, 075° ripple crest orientation) | 6.10 | 63.53 |
| 9b | Dolomitic lime wackestone: light grey, mottled, graptolites | 0.10-0.20 | 57.43 |
| 9a | Boundstone: thrombolitic boundstone mounds oriented 185°, fringed by grainstone that passes into highly bioturbated, thinly bedded wackestone–packstone–grainstone rich in gastropods, top of mounds may be locally eroded | 0.45 | 57.23 |
| 8i | Wackestone–packstone: dark grey uneven to evenly, thin bedded, bioturbated fossiliferous, planar stratified grainstone, robust fauna of gastropods, straight cephalopods and trilobites, graptolites 1.8 m from top | 2.90 | 56.78 |
| 8h | Grainstone–wackestone: ripple marks (035° ripple crest orientation), rich in trilobites | 0.25 | 53.88 |
| 8g | Dolomitic lime wackestone with mottled, thin beds and lenses of grainstone, some trilobites | 0.17 | 53.63 |
| 8f | Wackestone–packstone–boundstone: small mounds 5 to 10 cm in size, locally up to 20 cm diameter, surrounded by bioclastic packstone to wackestone rich in gastropods, opercula, crinoids and trilobites, mounds have a bioturbated, wackestone and skeletal-rich core surrounded by a dark-grey to black outer zone (thrombolite) 0.05 to 1 cm in thickness | 0.20 | 53.46 |
| 8e | Wackestone–packstone: burrow-mottled, bioclastic, rich in gastropods and cephalopods, some broad gentle undulose scours?, silicified grainstone, sphalerite in dolomite-filled vug | 2.93 | 53.46 |
| 8d | Lime mudstone: dolostone mottles, no stratification | 0.23 | 50.33 |
| 8c | Wackestone–packstone: dolomitic burrow mottling; several grainstone beds, internally planar stratified, some ripple marks (175° ripple crest orientation), rich in skeletal remains, including cephalopods, gastropods, brachiopods, silicified opercula, trilobites | 7.20 | 50.10 |
| 8b | Dolomitic lime wackestone: thin bedded, rich in large *Isotoloides*, brachiopods, graptolites, some grainstone lenses | 0.29 | 42.90 |
| 8a | Wackestone–packstone: uneven and even thin stratification, grainstone layers scattered throughout but common near base, some ripple marks (063° ripple crest orientation), some small mounds, large gastropods, straight to curved cephalopods, silicified opercula, trilobites; 20 cm wackestone bed 3.7 m above base | 10.83 | 42.61 |
| 7e | Mudstone–wackestone: wavy thin bedded, shaly, gutter casts (trend 055°), graptolites | 0.30 | 31.78 |
| 7d | Grainstone with mudstone flaser: crosslaminated, ripple marks (070° ripple crest orientation) rich in large *Isotoloides*, graptolites | 0.33 | 31.48 |
| 7c | Wackestone intercalated with packstone: strongly bioturbated having lenses and layers of grainstone surrounding small sinuous highs in wackestone | 0.58 | 31.15 |
| 7b | Wackestone–packstone: thinly stratified with grainstone layers rich in gastropods, planar stratified and carrying ripple marks (060°, 100° ripple crest orientation) | 3.84 | 30.57 |
| 7a | Wackestone: shaly, uneven thin bedding, fine burrows, gutter casts (trend 050°) | 0.30 | 26.73 |

| Unit | Description | Unit Thickness m | Cumulative Thickness m |
|---|---|---|---|
| 6 | Wackestone–packstone: thinly stratified, bioturbated, fossiliferous | 4.70 | 26.43 |
| | East- to southeast-trending fault zone several metres wide cuts the section coinciding with a rocky channel between Catoche Point and Catoche Island. The faults downthrow to the south but displacement and loss of section is not known with certainty. W.D. Boyce (personnel communication, 1985, 1986) comparing faunas of this section with that nearby at Barbace Cove-Barbace Point and at Hunters Point suggests Unit 6 begins approximately 22 m above the base of the Catoche Formation. This suggests approximately 9 m of section is missing across this fault | 9.00 | 21.73 |
| 5f | Wackestone–packstone: argillaceous, dolomitic, fossiliferous, bioturbated, wavy thin bedding, some scour-based rudstone and laminated, very fine-grained grainstone lenses, some small mounds 23 cm from top | 1.08 | 12.73 |
| 5e | Rudstone: intraclastic, reddened clasts, spar cement, sheet deposit, sharp base | 0.15 | 11.65 |
| 5d | Wackestone–mudstone with packstone lenses: argillaceous partings, lumpy to wavy thin bedding; intraclastic rudstone layers at 20 cm contain gastropods | 1.74 | 11.50 |
| 5c | Rudstone–wackestone: 10-cm-thick pebble beds of red intraclasts with spar cement alternating with burrowed wackestone, small conical mounds on top | 1.24 | 9.76 |
| 5b | Mudstone: wavy thin bedded and laminated, some pebbly intraclastic–bioclastic grainstone lenses in lower 40 cm, some small mounds | 0.42 | 8.52 |
| 5a | Wackestone alternating with rudstone and grainstone: bioturbated, thin-bedded wackestone alternating with sparry, intraclastic rudstone in lower 70 cm and crosslaminated, ripple-marked grainstone above | 1.30 | 8.10 |
| 4 | Rudstone: imbricated reddened, discoid lime mudstone intraclasts, spar cemented, crossbedded, thin wackestone drapes at intervals, planar top, erosive base | 0.65 | 6.80 |
| 3 | Wackestone–packstone: bioturbated, well-bedded with grainstone lenses, intraclastic rudstone beds interbedded with burrowed, wavy thin-bedded and flaser-bedded dolomitic lime mudstone in top 50 cm, base covered at sea level; Units 3 to 5 are separated from Units 1 and 2 on the north side of the island by a north-trending fault that downthrows to the east; comparison with section on the east side of Barbace Cove suggested the thickness of the missing section is probably less than 2 m | 4.10 | 6.15 |
| 2 | Boundstone: mounds rich in sponges, trilobites, gastropods, cephalopods, eocrinoids associated with spar-cemented grainstone | 0.55 | 2.05 |
| 1 | Wackestone–packstone: bioturbated, abundant fossils, small boundstone mounds 30 cm from base. | 1.50 | 1.50 |

Unit 1 conformably overlies mudcracked, laminated dolomitic lime mudstone unit forming top of the Boat Harbour Formation

# SECTION 10

## AGUATHUNA FORMATION–TABLE POINT FORMATION: Back Arm

East side of Back Arm, 0.6 km north of Port au Choix.

| Unit | Description | Unit Thickness m | Cumulative Thickness m |
|---|---|---|---|
| | TABLE POINT FORMATION (incomplete) | | |
| 13 | Wackestone–mudstone: thick bedded, blocky to rubbly weathering, grey, fossiliferous basal cyclic member | 6.4 | 18.17 |
| 12 | Lime mudstone: 1.35 m of unevenly thin-bedded, light-grey lime mudstone overlain by 0.40 m of more blocky-weathering, slightly dolomitic lime mudstone displaying uneven lamination with some laminar fenestra | 1.75 | 11.77 |
| 11 | Lime mudstone: 56 cm of massive-bedded lime mudstone overlain by 54 cm of unevenly laminated, lime mudstone, some laminar fenestra | 1.10 | 10.02 |
| 10 | Calcareous dolostone and dolostone: buff weathering, planar thin bedded passing down into lamination | 1.15 | 8.92 |
| 9 | Covered interval | 0.48 | 7.77 |
| 8 | Lime mudstone: grey, nodular | 0.90 | 7.29 |
| 7 | Lime mudstone: 85 cm of buff-weathering, grey, nodular lime mudstone overlain by 30 cm of laminated lime mudstone displaying disrupted 'mudcracked' laminae | 1.13 | 6.39 |
| 6 | Poorly exposed but top 67 cm is of buff weathering, grey dolostone | 1.32 | 5.26 |
| 5 | Argillaceous lime mudstone: massive, some suggestion of thin bedding and possible lamination; lichen covered | 0.73 | 3.94 |
| 4 | Covered interval | 0.90 | 3.21 |
| 3 | Lime mudstone: two beds of nodular, shaly stylolites | 0.91 | 2.31 |
| 2 | Argillaceous dolostone: grey, some lime mudstone mottles, nodular | 0.33 | 1.40 |
| 1 | Dolomitic lime mudstone: grey, massive to poorly bedded | 1.07 | 1.07 |
| | AGUATHUNA FORMATION | | |
| 4 | Argillaceous, dolomitic lime mudstone and dolostone: dolostone in basal 50 cm only, dolostone and lime mudstone mottles, hackly to blocky weathering, bioturbation sparse, trilobites (*Bathyurus perplexus* Billings), ostracods and brachiopods, suture-like, uneven solution pitted upper bedding surface | 0.90 | 5.07 |
| 3 | Dolostone: beds of finely laminated alternating with massive dolostone, slightly mottled dolostone | 1.65 | 4.17 |
| 2 | Dolostone: bedded, light yellow weathering, light grey, apparently massive with undulose, uneven to 'suture-like' solution pitted bedding planes, some mudcrack polygons seen in fallen blocks | 1.52 | 2.52 |
| 1 | Covered interval: apparently yellow-weathering, bedded dolostone | 1.00 | 1.00 |
| | Base of Aguathuna Formation is apparently conformable with underlying epigenetic dolomites, Unit 149 of the Catoche Formation, Bustard Cove Section | | |

Total thickness of section is 23.24. Aguathuna dolostones = 5.07 m at base. Basal Table Point lime mudstones and dolostones = 18.17.

# APPENDIX 2

# Descriptive Summary of Stratigraphic Units of Study Area

## LABRADOR GROUP (Early to early Medial Cambrian)

FORMATION NAME: **BRADORE FORMATION** AGE: Early Cambrian FOSSILS: rare trace fossils

THICKNESS: Up to 120 m. **UNCONFORMABLE** upon regolith and Precambrian surface with considerable topographic relief

| LITHOLOGY | PETROLOGY | DEPOSITIONAL ENVIRONMENT |
|---|---|---|
| A. **Arkosic sandstone, pebbly sandstone and basal conglomerate**, red and brown planar and trough crossbedded, fine to coarse grained | Quartz, microcline, microcline–perthite, plagioclase, rare muscovite, magnetite, zircon, sphene and rare tournaline | Braided fuvial draining eastward |
| B. **Micaceous sandstone** grey and pink-grey, thick to thin bedded, laminated, rare burrows including *Skolithus*, very fine to fine grained | Quartz, microcline, perthite muscovite, biotite, chlorite-clay matrix, rare heavy minerals some glauconite | Shallow marine, nearshore–shoreface, estuarine |
| C. **Quartzose sandstone**, white to pink, crossbedded, abundant *Skolithus linearis* | Well sorted | Shallow marine, high energy, nearshore |

FORMATION NAME: **FORTEAU FORMATION** AGE: Early Cambrian (middle *Bonnia-Olenellus* Zone)

FOSSILS: Trilobites, inarticulate and articulate brachiopods, archeocyathids, salterellids, hyolithids, crinoids, trace fossils

THICKNESS: 115 m. **CONFORMABLE, SHARP** contact with Bradore Formation

### DEVIL'S COVE MEMBER 6 m thick

| LITHOLOGY | DEPOSITIONAL ENVIRONMENT |
|---|---|
| **Limestone**, red, pink and grey, nodular, shaly, locally fossiliferous to grainy **dolomite**, some *Salterella* | Basal transgressive subtidal carbonate muds to intertidal carbonate sands |

### MIDDLE SHALE MEMBER 40 m thick

| | |
|---|---|
| A. **$K_2O$-rich shale**, black, purplish-grey, rich in trilobite layers, nodular fossiliferous limestone at discrete horizons, some burrow horizons | Quiet, deep shelf with anoxic bottom muds, storm-generated fossiliferous carbonate beds, frequent mass mortality of benthonic trilobites |
| B. **Shale and interbedded bioturbated, very fine sandstone**, grey some crosslamination, planar and wavy lamination preserved in sands, 10- to 30-cm-thick beds, abundant and diverse trace fossil assemblage | Shallow subtidal shelf with storm-generated sands extensively bioturbated during fairweather |

## LABRADOR GROUP

### UPPER LIMESTONE MEMBER 60 m thick

| LITHOLOGY | PETROLOGY | DEPOSITIONAL ENVIRONMENT |
|---|---|---|
| A. **Archeocyathid build-ups**, metre-sized reefs of stick- and cup-shaped archeocyaths with *Renalcis* and *Girvanella;* associated with skeletal grainstones and rudstone, abundant skeletal material, crinoid ossicles | Framework builders encrusted by blue-green algae having fibrous, micritic and sparry marine cements, plus carbonate mud in cavities | High-energy, open marine nearshore setting |
| B. **Calcareous sandstone–arenaceous limestone**, crossbedded, westward paleoflow, reactivation surfaces, metre-thick units of grey shale interbeds | Quartz-rich sandstone, well sorted, fine to medium grained, oolitic, some *Salterella*-rich layers | High-energy, subtidal, linear sand bodies formed by accretion of dunes |
| C. **Oolitic lime grainstone**, oolites with skeletal and oncolitic grains, crossbedded, planar bedded, crosslaminated, some bioturbation, dolostone lenses, rip-ups of dolostone and oolitic limestone | | High- to moderate-energy nearshore to shoreline tidal sandbodies and shoals |
| D. **Grey shale and calcareous sandstone**, massive sands that are commonly bioturbated, contain *Salterella* and trilobites | Glauconitic, poorly sorted sands | Deeper water 'open shelf' |

FORMATION NAME: **HAWKE BAY FORMATION** AGE: Late Early Cambrian to early Medial Cambrian

THICKNESS: 150 m. **CONFORMABLE** upon Forteau Formation FOSSILS: trilobites, hyolithids, trace fossils

| LITHOLOGY | PETROLOGY | DEPOSITIONAL ENVIRONMENT |
|---|---|---|
| A. **Quartz arenite**, white, pink to green, some quartz pebbles, large planar and medium trough crossbeds, ripple marks syneresis cracks in green shale partings, local water escape, no bioturbation | Very fine- to medium-grained, well-sorted, common quartz, some microcline and orthoclase, heavy mineral laminae of magnetite, zircon and sphene, silica cement | High energy, tidal-dominated, subtidal to intertidal, sand flat, mostly northeast to east paleoflow |
| B. **Bioturbated quartz sandstone**, grey, red and white, argillaceous, flaggy beddings, planar lamination, shale partings and thin beds, ripple marks, parting lineation, extensive bioturbation, syneresis cracks | Glauconite, pyrite, quartz plus some microcline in sericite muscovite and chlorite matrix | Intertidal, lower energy areas of tidal sand flat with intermittent storm deposits |
| C. **Interbedded siltstone–sandstone**, uneven to planar thin bedded, flaser bedding, intraformational conglomerate with phosphate pebbles, burrows rare | | Intertidal mud flat |
| D. **Shale plus thin sandstone**, green-grey, fossiliferous and bioturbated, sands are planar laminated with some ripple marks, some shale and phosphatic pebbles, sandstone dykes, trilobites and hyolithids | Sands are well sorted, glauconitic | Deep subtidal shelf muds with low density turbidites, part of upward shoaling–coarsening sequence |

## PORT AU PORT GROUP (Late Middle Cambrian to late Late Cambrian)

FORMATION: MARCH POINT FORMATION AGE: Late Middle Cambrian FOSSILS: inarticulate brachiopods, trace fossils

THICKNESS: 29 m. CONFORMABLE, SHARP upon Hawke Bay Formation

| LITHOLOGY | PETROLOGY | DEPOSITIONAL ENVIRONMENT |
|---|---|---|
| Shale, dolostone sandstone, siltstone | | |
| A. **Basal shale** having interbedded thin sandstone, siltstone with quartz and phosphatic pebbles, inarticulate brachiopods, some bioturbation | | Intertidal probable |
| B. **Dolostone**, dark grey, thin-bedded, laminated, bioturbated, lenses of intraformational conglomerate, gutter casts, rare inarticulate brachiopods | | Intertidal flat to shallow subtidal |
| C. **Shale, shaly dolostones and dolostone**, thin-bedded, laminated, ripple marks, mudcracks, fenestra, some stromatolites, tepee structures | | Intertidal–supratidal flat, possible intertidal or supratidal ponds |

FORMATION: PETIT JARDIN FORMATION AGE: Early Late Cambrian to Late Cambrian.

THICKNESS: 400 m (outside of area). CONFORMABLE upon March Point Formation FOSSILS: trilobites, inarticulate brachiopods

| LITHOLOGY | PETROLOGY | DEPOSITIONAL ENVIRONMENT |
|---|---|---|
| Dolostone, shale, limestone | | |
| A. **Lower dolostone member. Dolostone and shale**, pale grey, thin-bedded dolostone, intraclastic dolrudite, mudcracks, ripple marks, lamination, crosslamination, planar to pan-shaped stromatolites, fissure cracks | | Intertidal to supratidal, low energy, tidal flat |
| B. **Stromatolite member. Dolostone**–pale grey, digitate, domal, columnar and flat stromatolites, crossbedded oolitic grainstone, skeletal-intraclastic rudstone filling channels, thin-bedded, laminated and crosslaminated dolostone, mudcracked | | High- to low-energy, intertidal settings including mounds fringed by oolitic shoals, intertidal flats crossed by channels |
| C. **Upper dolostone member. Dolostone**, light grey to grey, some sand grains and laminations, thin to thick bedded, mottled, laminated and stromatolitic beds, poorly exposed | | Subtidal to intertidal flat, windblown quartz sand |
| D. **Cherty dolostone member** (to be called **BERRY HEAD FORMATION**) | | |

### PORT AU PORT GROUP

AGE: Late Cambrian THICKNESS: unknown

| LITHOLOGY | PETROLOGY | DEPOSITIONAL ENVIRONMENT |
|---|---|---|
| **Dolostone**, grey to blue grey, cherty, thick bedded, some dark grey stromatolitc dolostone, some oolitic beds, poorly exposed everywhere in area | | |

## ST. GEORGE GROUP (Early to early Middle Ordovician; Canadian to Whitrockian)

FORMATION: WATTS BIGHT FORMATION AGE: Early Canadian (Gasconadian, early Tremadocian)

THICKNESS: 90 m. CONFORMABLE, SHARP upon Port au Port Group FOSSILS: Scarce cephalopods, conodonts, trilobites, gastropods

| LITHOLOGY | PETROLOGY | DEPOSITIONAL ENVIRONMENT |
|---|---|---|
| A. **Dolostone**, dark tan-grey burrow-mottled, and thrombolitic and stromatolitic mounds, chert common, some dololaminites, rare molluscs | Equigranular, hypidiotopic, crystalline, peloidal texture in some cherts | Subtidal with some intertidal beds; most of formation replaced by crystalline dolostone. |
| B. **Limestone**, white, thrombolite mounds with *Renalcis, Girvanella* and *Lichenaria*, surrounded by intraclastic-skeletal grainstone with large oncolites, trilobites, gastropods | Peloidal micrite thromboids with blue-green algae and corals | |

FORMATION: BOAT HARBOUR FORMATION AGE: Early to early late Canadian (Deminigian to early Cassinian, late Tremadocian–early Arenigian)

FOSSILS: Locally common trilobites, conodonts, brachiopods, gastropods, cephalopods, crinoids

THICKNESS: 105 m. CONFORMABLE on Watts Bight Formation

| LITHOLOGY | PETROLOGY | DEPOSITIONAL ENVIRONMENT |
|---|---|---|
| Peritidal limestone, dolostone, minor dolomitic sequences | | |
| A. **Bioturbated lime wackestone lithofacies**, thin bedded, bioturbated, some lamination, thin beds and lenses of skeletal packstone-grainstone, fossiliferous | Peloidal, disintegrated peloids, some microspar cement in grainstone | Shallow subtidal |
| B. **Packstone - grainstone lithofacies:** i) **oolitic grainstone**, ripple marked silicified, oolitic intraclasts, fossiliferous | Ooids mostly, recrystallised, and silicified, some radial fibrous cores with concentric cortices | Intertidal, possible storm layers |
| ii) **Skeletal–intraclastic grainstone**, large sinuous ripple marks, sheets, some truncated tops to beds, crossbedded | Neomorphism, micritized edges to skeletal grains, fringing blocky to radiating microspa-cements, syntaxial cement on crinoid ossicles | |

## ST. GEORGE GROUP

| LITHOLOGY | PETROLOGY | DEPOSITIONAL ENVIRONMENT |
|---|---|---|
| C. **Limestone mudstone and dolostone lithofacies:** | | |
| i) **Wavy thin bedded limestone–dolostone,** flaser bedding, lenticular bedding, wavy thin bedding, some bioturbation, *Chondrites, Palaeophycus* and *Planolites,* scour and fill, crosslamination, small-scale ripple marks, some fenestra, minor mudcracks, small mounds, some lenses of intraformational breccia | Peloidal micrite, stylolitic | Intertidal flat, low to high |
| ii) **Dololaminite,** calcareous, planar lamination, subtle discontinuity surfaces, mudcracks, fissure and sheet cracks, some silicified and dolomitized nodules. Intertidal to supratidal with minor displacive evaporites | | Intertidal to supratidal with minor displacive evaporites |
| iii) **Shaly dolomitic lime mudstone,** thinly bedded to nodular, small ripple marks, mudchip pavements, oriented wrinkle marks, brittle fracturing of mudstone compacted over associated stromatolite mounds | | Intertidal flat, soft sediment deformation, early lithification |
| D. **Boundstone lithofacies:** Light to grey to dark grey limestone | | |
| i) **Stromatolites,** large domal mounds of columnar, digitate, aberrant and lateral-linked forms; small irregular mounds of lateral-linked hemispheroids; low flat pancake-shaped mounds of flat to marginally recumbent lamination associated with intertidal facies C | Alternating laminae of micrite, fenestra-rich micrite, clotted micrite | Subtidal to intertidal as isolated mounds or nested clusters |
| ii) **Thrombolitic,** large digitate to clotted textures, *Renalcis* bushes in some mounds. Fringed by grainstone and by facies A wackestone; nucleate on intraclastic substrata | Clotted fabric, *Renalcis*-like bushes, *Renalcis* with fine dolomicrite sediment between bushes; some mounds are gastropod-rich | Subtidal mound complexes of oriented nests and open banks |
| E. **Exposure surfaces and sandy pebbly dolostone,** thin lag breccia or sand and pebble veneer of dolostone and chert, above locally brecciated and fractured carbonate that is extensively dolomitized | Some chalcedony, megaquartz, some clasts have blackened edges | Exposure surface with surface karstification, formation of rubble regolith, minor resedimentation |

## ST. GEORGE GROUP

FORMATION NAME: **BARBACE COVE MEMBER** AGE: Middle Canadian (late Jeffersonian to early Cassinian, early Arenigian)

THICKNESS: 12 m. **DISCONFORMABLE BASE**

| LITHOLOGY | PETROLOGY | DEPOSITIONAL ENVIRONMENT |
|---|---|---|
| Parted dolomitic limestone, ripple-marked and crossbedded, skeletal-intraclastic grainstones and rudstone, bioturbated wackestone and laminated and mudcracked, dolomitic and locally shaly lime mudstone, cryptalgal laminite and dololaminite. Markedly fossiliferous. Some truncation surfaces associated with underlying brecciation and locally overlying pockets of conglomerate in the lower part of the member | | Mixed high- to low-energy tidal flat with lithification and exposure |

FORMATION NAME: **CATOCHE FORMATION** AGE: Middle to late Canadian (Cassinian, Arenigian

THICKNESS: 160 m. **CONFORMABLE** on Boat Harbour Formation

FOSSILS: Abundant trilobite, brachiopods, cephalopods, ostracods gastropods, conodonts, some sponges, receptaculitids, crinoids

| LITHOLOGY | PETROLOGY | DEPOSITIONAL ENVIRONMENT |
|---|---|---|
| Well-bedded, bioturbated, fossiliferous dolomitic limestone and some thrombolite mounds, minor nodular calcareous dolostone | | |
| A. **Bioturbated mudstone to grainstone lithofacies**, planar to uneven thin bedded, bioturbated fossiliferous | Peloidal micrite recrystallized to microspar, skeletal grains locally, *Girvanella, Nuia* | Subtidal, biomechanically homogenized, open shelf carbonate sediment |
| B. **Packstone–grainstone lithofacies**, mostly lenses with ripple-marked tops and scour bases, rich in intraclasts and fossils, cross-stratified | Peloids, skeletal grains, clasts of mudstone–packstone, *Girvanella, Nuia*, mostly blocky spar cements, some shelter porosity with bladed pendant and radiaxial cements | Storm-sorted layers, shelf setting |
| C. **Dolomitic lime mudstone–wackestone lithofacies**<br>i) **dolomitic wackestone**, burrow mottled, nodular, with graptolites and *Isotoloides*, or<br>ii) flaser bedded and thin bedded | | Shallow subtidal to intertidal |
| D. **Intraclastic rudstone lithofacies**, discoidal carbonate pebbles, some reddish, large skeletal remains scour-based, cross-stratified, some reactivation surfaces | | Subtidal channel |

## ST. GEORGE GROUP

| LITHOLOGY | PETROLOGY | DEPOSITIONAL ENVIRONMENT |
|---|---|---|
| E. **Boundstone mound lithofacies,** irregular to linear thrombolitic mounds, surrounded by narrow grainstone fringe and facies A; contain sponges, receptaculitids, large molluscs trilobites, brachiopods and crinoids | Micrite-microspar, clots *Renalcis*-like bushes, *Girvanella*, micritized skeletal grains, sponge spicules, some cavities cemented by blocky spar, or radiaxial mosaic cements. | Subtidal mound banks, locally current oriented north to south |

FORMATION NAME: **AGUATHUNA FORMATION** AGE: Mostly Whiterockian; Canadian strata in southeast.

THICKNESS: 3 to 15 m. **UNCONFORMABLE ONLAP** on Catoche Formation FOSSILS: Trilobites, ostracods, conodonts

| LITHOLOGY | PETROLOGY | DEPOSITIONAL ENVIRONMENT |
|---|---|---|
| **Microcrystalline, pale grey dolostone, minor shale, basal chert-pebble conglomerate locally,** dolostone locally preserves lamination, mudcracks, egg-carton stylolites, vague mottling, neptunian dykes that cut deep along northeast-trending joints and faults into Catoche Formation and filled with chert and dolomitic mudstone and sandstone of Aguathuna Formation, penecontemporaneous folding and brittle fracturing of formation locally | Xenotopic to hypidiotopic dolomite, quartz silt, megaquartz nodules rich in inclusions and fibrous textures, chert pebbles at base include evaporitic textures | Arid tidal flat, carbonate deposited during tectonically unstable period, upon block-faulted and karsted platform |

## TABLE HEAD GROUP (Whiterockian, early Middle Ordovician)

FORMATION NAME: TABLE HEAD FORMATION AGE: Whiterockian (Llanvirnian)

THICKNESS: 100 to 120 m. CONFORMABLE upon St. Georges Group

FOSSILS: Trilobites, cephalopods, brachiopods, ostracods, gastropods, bryozoans, sponges, conodonts

| LITHOLOGY | PETROLOGY | DEPOSITIONAL ENVIRONMENT |
|---|---|---|
| Dark grey, fossiliferous, massive to lumpy bedded, shaly limestone, minor dolostone | | |
| A. **Cyclic lithofacies,** massive to nodular limestone, dolostone, laminated and fenestral lime mudstone, ostracods, some mudcracks, 1 to 3 m beds, shallowing-upward sequences | Wackestone with ostracods, fenestra cemented by fibrous and equant cements, some pendant cements, laminite of peloidal micrite plus ostrocods, *Garwoodia, Girvanella* and *Renalcis,* micritized skeletal grains | Peritidal, humid tidal flat |
| B. **Fenestral limestone lithofacies,** pale grey, massive to fenestral limestone, bioturbated, skeletal wackestone with large molluscs and tubular fenestrae, fenestral, locally laminated, mudstone, stromatactoid–voids | Wackestone–peloidal, molluscs replaced by spar, fenestral limestone-blotchy micrite with ostracods, fenestra cemented by clear equant spar, stromatactoid voids contain radiaxial fibrous cements and geopetal mud | Humid peritidal setting |
| C. **Bioclastic wackestone–packstone lithofacies,** dark grey well bedded, fossiliferous, bioturbated, locally sponge–bryozoan-pelmatozoan bioherms with grainstones locally crossbedded, locally slump folds and breccia | Peloidal, skeletal micrite, *Nuia,* micritized grains with *Girvanella,* neomorphism of matrix; peloids and *Halysis* in grainstone, micritized grains | Subtidal, open marine, shelf, tectonically unstable |

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